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Report on Carbon and Nitrogen Abundance Studies

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Carbon and Nitrogen Abundances in Stars.

The aim of the proposal was to determine the nitrogen to carbon abundance ratios from transition layer lines in stars with different T_{eff} and luminosities.

The surface emission line fluxes F are given by

$$F = \Omega(T, \text{line}) \cdot Em(T) \cdot Ab(\text{element})$$

where Ω gives the collisional excitation rate for the line under investigation for the temperature at which the line is predominantly formed. Ab(element) is the abundance of the element under investigation and

$Em(T) = \int_{h_1}^{h_2} n_e^2 \, dh$ is the emission measure, with n_e = the electron density

and the heights h_1 and h_2 bracket the height range at which the line is predominantly formed. When F is measured and $\Omega(T, \text{line})$ is known from theory or experiment the product Em(T)·Ab(element) can be determined. For stars with known element abundances the Em(T) can be determined for different temperatures from lines formed at different temperatures. For main sequence and luminosity class IV stars with supposedly solar element abundances it was found that the dependence of the emission measures on temperature follows a power law for the temperature range 30,000K < T < 150,000K. We determine the exponent of the power law for each star from the ratio of the CII to CIV emission measures which is independent of the element abundance. These lines originate at very different temperatures (30,000K and 100,000K). With the known exponent in the power law we can extrapolate the emission measures to T=150,000K, the temperature at which the NV lines are formed. For stars for which we do not know the abundance of carbon the carbon lines only give us the product of Em(T)·Ab(carbon) which we extrapolate to 150,000K.

The mwasured ratio of the NV to CIV emission line fluxes is given by

$$\frac{F(NV)}{F(CIV)} = \frac{(NV)}{(CIV)} \frac{Em(NV)}{Em(CIV)} \frac{AB(N)}{Ab(C)}$$

from which the abundance ratio N/C can be determined. (The unknown factor of the carbon abundance is attached to both the Em(CIV) and the extrapolated Em(NV) and therefore cancels.) We previously reported our results for giants.

Some colleagues have expressed concerns whether the power law extrapolation of the emission measures to T=150,000K is justified for the giants studied by us. We have checked this again for several FV and FIV stars with solar abundances and the fit is quite good. As a further check we have compared our

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abundance results with those of photospheric abundance studies for stars in common with the photospheric investigations. The results are shown in Figure 1, which, I think shows that our analyses are at least as accurate as the photospheric determinations. Our studies can be extended to F and early G stars for which photospheric abundance determinations for giants are hard to do because molecular bands become too weak. We estimate the upper limit for our errors to be 0.27 dex, which could occur only if all the errors conspire to work in the same direction which is rather unlikely. We have submitted the abundance results for publication in the Ap.J. I enclose a copy of the manuscript.

We have then looked at the abundance determination in the context of stellar evolution. As already shown in the last report the N/C abundance ratio increases steeply at the point of evolution for which the convection zone reachest deepest. Looking at the evolution of the rotation velocities v sin i we also find a steep decrease in v sin i at this point, which makes it rather likely that the decrease in v sin i is related to the increasing depth of the convection zone.

The evolutionary timescales for the giants are rather short. Rutten and Pylyser (1988) estimate by comparison with main sequence stars that these timescales are too short for magnetic braking due to stellar winds to cause the decrease in v sin i during such a small interval of T_{eff}. This leaves two possibilities: Either the deep convection zone leads to much larger magnetic activity than for main sequence stars thereby leading to enhanced fast braking or the surface angular momentum is reduced due to rearrangement of angular momentum within the star caused by the deep convection. If the star started out rotating nearly as a rigid body and convection brings deep material to the surface as indicated by the increased N/C abundance ratio, it brings at the same time lower angular momentum material to the surface. The surface v sin i is then expected to decrease as already pointed out by Endal and Sofia. For rotation with nearly depth independent angular momentum in the deep convection zone Endal and Gray (1982) calculate a surface v sin i as indicated by the squares shown in Figure 2 ,assuming an original v sin i = 140 km/sec. as observed in the average for the main sequence progenitors. This point fits the observations rather well.

On the other hand if increased magnetic activity due to deep convection is responsible for the fast braking we may expect to see increased transition layer activity and increased coronal temperatures leading to stronger stellar winds. We have checked this. No increased transition layer emission is seen at the point where v sin i decreases and no increased X-ray emission is seen either. We conclude that the decrease in v sin i for $T_{eff} \lesssim 5800$ K is most probably due to the rearrangement of angular momentum in the stars due to deep convective mixing. It appears that the convection zone is rotating with nearly depth independent angular momentum.

If the angular momentum of the star does not change at this point, yet a steep decrease in magnetic activity is seen as observed in the CIV lines, then this shows that the dynamo responsible for the transition layer activity is seated mainly in the surface layers of the star which has the low v sin i. The high v sin i value in the deeper layers has apparently no influence. The same holds for the magnetic field responsible for the coronal X-ray emission.

We have written up these discussions in a paper submitted to the A.J. for publication. A copy is enclosed.

We have now extended the abundance studies to luminosity class IV stars. For these stars the transition layer emission is generally weaker. The measuring uncertainties therefore become larger. The general trend for the N/C abundance ratios still agrees with expectations from stellar evolution theory. We find an average increase in the N/C abundance ratio at the point of deepest convection. Since these stars are generally older than the giants they have lost already some angular momentum while on the main sequence. The decrease in v sin i at the evolutionary state with rapidly deepening convection still seems to be there but is less well pronounced. Evolutionary timescales along the subgiant branch are somewhat longer thereby permitting the magnetic braking to be more effective. On the other hand the activity for these stars is generally lower than for the giants. Rutten and Pylyser argue that because of this the magnetic braking also does not explain the decrease in v sin i for the subgiants. For the subgiants we are still in the process of analysing the relation between the different observational data and the interpretation in terms of stellar evolution.

We are also in the process of determining the N/C abundance ratios for main sequence stars for which the emission line fluxes are still smaller and very few well exposed spectra are available. The NV lines are very difficult to measure. For some FIV and FV stars very broad and complex features are seen in the 1240 A spectral region, which we have not yet been able to interprete. The N/C abundance ratios found for the cooler main sequence stars show a large scatter due to the measuring uncertainty. For the best spectra the average values seem to be the same for all spectral types as is to be expected, though the average N/C ratio appears to be higher by 0.1 dex than for the giants. This effect is more pronounced for the poorer spectra with hard to measure NV lines. We therefore suspect that for weak lines we tend to measure systematically somewhat too large emission line fluxes possibly interpreting a noise peak as a line. We are still in the process of studying this problem.

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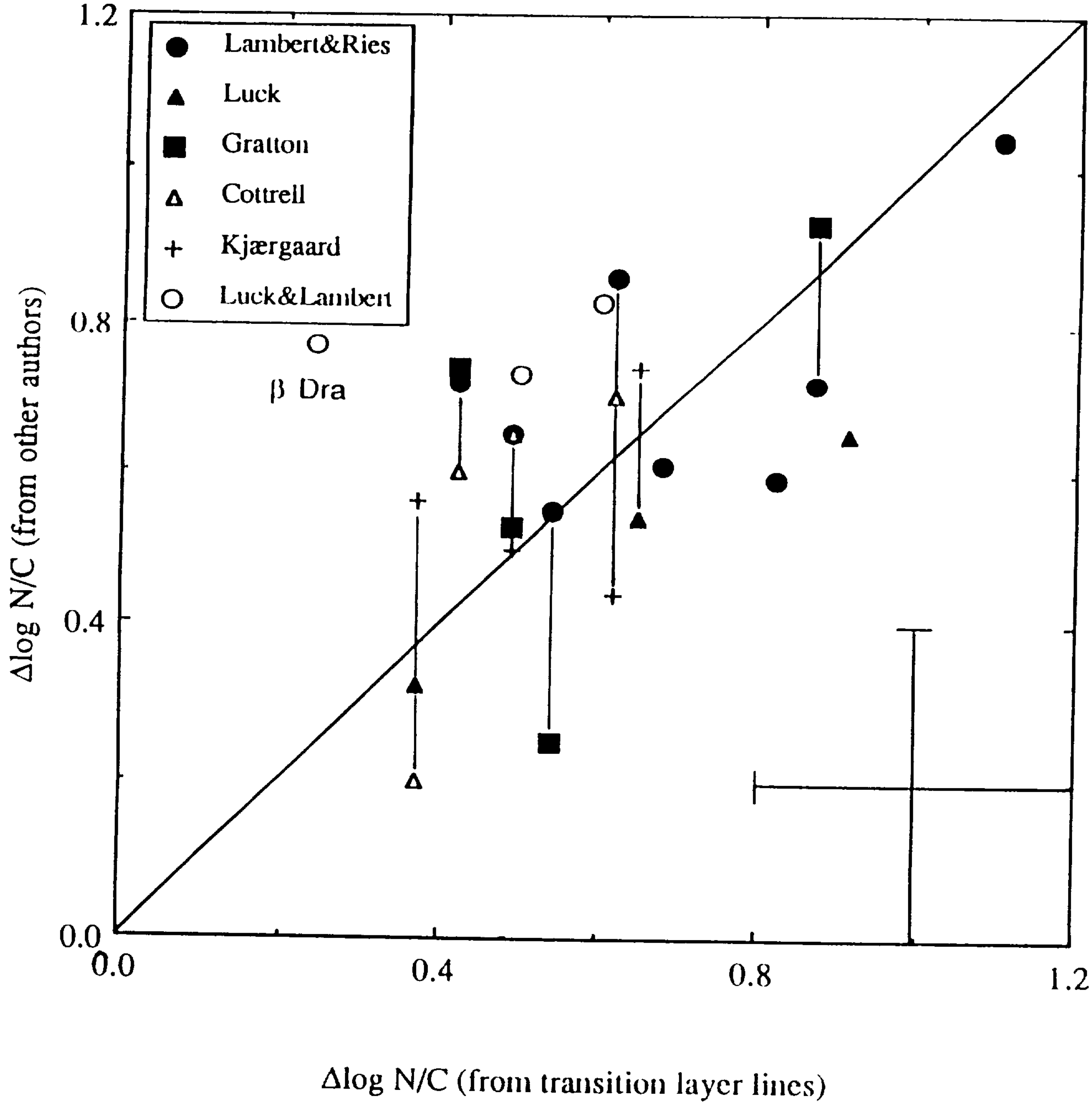


Figure 1. The photospheric excess abundance ratios, as compared to solar abundance ratios of nitrogen to carbon, obtained by other authors, are compared with the ones found here from the transition layer lines. The limits of error for both our study and the traditional approach of the other studies are shown in the lower right corner. The diagonal solid line would be obtained for perfect agreement. All stars are giants except the open circles which are supergiants from the Luck and Lambert (1985) paper.

Figure Caption

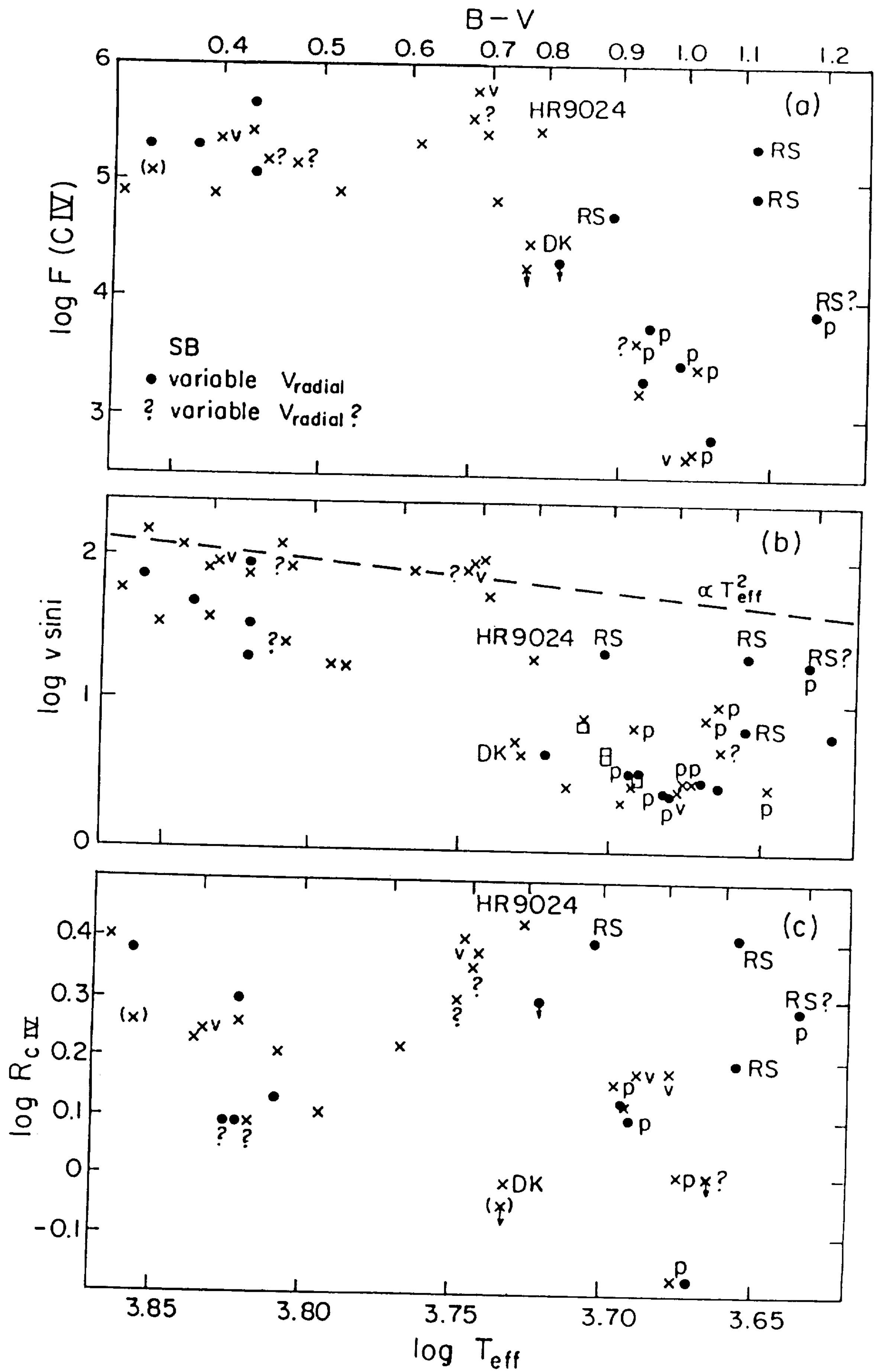
Figure 2a. The dependence of the C IV (1550 Å) emission line surface fluxes on the effective temperature is shown for giants. Dots indicate known spectroscopic binaries, v indicate variable radial velocities and question marks possible variable radial velocities for the stars. RS indicates RS CVn stars, p stars with peculiar CN and/or CH molecular band strengths. Brackets signal uncertain measurements, and arrows show that the values given are upper limits.

Figure 2b. The measured rotational velocities v sin i are shown as a function of T_{eff} or B-V. T_{eff} scale is the same as in Figures 1a and 1c. Notation as in Figure 1a. Notice that the peculiar CN and CH molecular band strength are observed only after the stars have decreased their v sin i.

The dashed line indicates the expected decrease in v sin i due to expansion if each mass element were to conserve its angular momentum (see text).

The values calculated by Gray and Endal (1982) for v_0 sin i = 140 kms^{-1} and for depth independent specific angular momentum in the convection zones are given as squares.

Figure 2c. The logarithm of the C IV to C II line flux ratio $R_{CIV} = \log \frac{F(CIV)}{F(CII)}$ is shown as a function of log T_{eff}. Notation is the same as in Figure 1a. The ratio decreases for slowly rotating stars, probably showing a smaller contribution of MHD wave heating. γ Tau was omitted from the plot because of the large variations in R_{CIV}.



E. Böhm-Vitense

Figure 2

Carbon and Nitrogen Abundances Determined from Transition Layer Lines

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Abstract

We explore the possibility to determine relative carbon, nitrogen and silicon abundances from the emission line fluxes in the lower transition layers ($3 \cdot 10^4\mathrm{K} < T < 1.5 \cdot 10^5\mathrm{K}$) between stellar chromospheres and coronae. The surface fluxes of the transition layer emission lines are proportional to the emission measures E_m and the element abundances A(el). Observations for main sequence and luminosity class IV stars with presumably solar element abundances show that for the lower transition layers *i.e.*, for $T \lesssim 1.5 \cdot 10^5\mathrm{K}$, $E_m = BT^{-\gamma}$. This is also expected from theoretical considerations. We assume that this relation also holds for s stars with nonsolar element abundance ratios. For a given carbon abundance the constants γ and B in this relation can then be determined from the C II and C IV emission line fluxes. The emission measures are thus known for all temperatures between $3 \cdot 10^4$ and $1.5 \cdot 10^5$K. From the N V and Si IV lines we can thereby determine the abundances of these elements relative to carbon from their surface emission line fluxes.

Ratios of N/C abundances determined in this way for some giants and supergiants agree within the limits of errors with those determined by Luck, Luck and Lambert, and Lambert and Ries from molecular bands. For giants we find an increase in the ratio of N/C at B-V ~ 0.8 as expected theoretically. We also find some apparent changes in the silicon to carbon abundance ratios.

Subject headings: stars: abundances – stars: emission-line – stars: late-type.

I. Introduction and Background

In 1978, 1981, and 1985, Luck and Luck and Lambert found in the atmospheres of supergiants and of Cepheids large N/C ratios coupled with increased C^{13}/C^{12} ratios indicative of CNO cycle processed material being mixed up to the surface of these stars.

These peculiar C and N abundances drew the attention of Becker and Cox in 1982. They studied whether such an enrichment in the nitrogen abundances in supergiants would be expected in the course of standard stellar evolution theory. They found that while mixing due to deep surface convection during the red giant phase dredges up some CNO cycle products the expected increase in the N/C ratio is smaller than the observed one. They found that the observed large increase in the N abundance could only be obtained theoretically if additional mixing above the boundaries of the convective core would occur in the progenitors of the supergiants and Cepheids during their main sequence phases. The material being mixed out from the core can then later be dredged up by deep surface convection during the red giant phase.

In 1981 Lambert and Ries also found larger than solar N/C ratios in giants. These findings were confirmed by Brown (1987). See also Luck (1991). These authors found an increase in N/C for $B - V > 0.65$. While the convection zone extends smoothly into deeper and deeper layers noticeable amounts of CNO cycle processed material can be dredged up only from very deep layers, close to the hydrogen burning shell source, which are reached by the convection only for $T_{\rm eff} \lesssim 5500$ K. Lambert and Ries, Brown and Luck also find larger increases in the N/C abundance ratios than would be expected theoretically.

Sneden, Pilachowski and VandenBerg (1986) studied the $^{12}C/^{13}C$ ratio and find indication for additional mixing during the main sequence phase also for population II giants, which means for stellar masses $\lesssim 1\ M_{\odot}$.

If additional mixing during the main sequence stage of massive stars actually takes place, it has very important consequences for stellar evolution theory. As was first pointed out by

Becker and Cox in 1982, and later also calculated by Bertelli, Bressan, Chiosi and Angerer (1986) such mixing leads to a widening of the upper main sequence as compared to standard evolution theory. It also leads to an increase of the main sequence lifetimes as compared to standard evolution theory. In addition it leads to an increase in luminosity for the giant phase for a star of a given mass and it especially leads to an increase of the luminosities of the Cepheids of a given mass. The evolutionary masses of Cepheids are thereby decreased and could then be in good agreement with the pulsational masses obtained for the distance scale determined by Schmidt (1984).

Luck and Lambert and Sneden *et al.* determined the C and N abundances from photospheric spectral analysis especially of molecular bands, which requires spectrum synthesis. An accurate knowledge of the temperature stratification is required as well as the knowledge of the oxygen abundance which is difficult to determine. LTE is always assumed. On the other hand, Lambert and Ries think that they see indications for NLTE effects in the strengths of the Fe lines in red giant atmospheres.

For supergiants Luck and Lambert used high excitation C and N lines to determine the abundances. These lines might also be vulnerable to NLTE effects. We might then perhaps wonder whether the abundance determinations can be trusted for giants and supergiants.

Since early interior mixing in stars appears to be very important for the whole evolutionary track and especially for the mass luminosity relation for later stages of stellar evolution, it seems to be very valuable to confirm it in another, independent way and also study for which stars it does occur and whether the degree of main sequence interior mixing depends on stellar masses or on rotation or perhaps the binary nature of stars.

Such a possibility is offered by the C II, C IV, Si IV and NV emission line fluxes originating in the transition regions between stellar chromospheres and coronae of cool stars. These lines permit abundance determinations also for F and early G stars which are too hot for the CN molecular bands to be studied.

The possibility to determine relative abundances from transition layer emission lines was first pointed out by Pottasch (1963), who found that for the sun the high ionization Fe lines were too strong in comparison with other lines if Fe abundances were used as accepted at the time for the solar photosphere. Higher abundances were required. It is well known that this discovery lead to the large revision of the Fe oscillator strengths and photospheric Fe abundances.

In their study of the emission measures for transition layer emission lines of bright giants and supergiants, Hartmann, Jordan, Brown and Dupree (1985) find that for solar abundances the Si III/C III] emission line ratios lead to densities which are inconsistent with those derived from the C II doublet lines at 2326 Å. They found that this discrepancy can be removed by using so-called "evolved" abundances as determined by Luck and Lambert and collaborators with $\Delta\log$ (N/C) = 0.67 as compared to the solar value.

II. Observational Data

In this study we concentrate on transition layer emission lines in giants. For population I giants we expect similar abundances for the main sequence predecessors. According to theory we expect changes in the nitrogen to carbon abundance ratios for evolved stars. The study of giants also offers the possibility to compare our results with those of Luck, Lambert and collaborators. Data for the C II (1335 Å), C IV (1550 Å), Si IV (1394 Å), N V (1240 Å) emission lines were collected from the literature. We mainly used data from Ayres *et al.* (1981), from Oranje (1986) from Rutten (1987) and from Simon and Drake (1989). We added our own measurements from newer IUE spectra and remeasured older spectra to compare our measurements with those of other authors. In Table 1 we collect the basic data for the stars for which we measured or remeasured the fluxes of the emission lines. In Table 2 we give the angular radii and the surface fluxes as determined by us. In Table 3 we give the surface fluxes for giants as determined by other authors. We only list values for spectra for which we estimate the measuring errors in the line flux ratio $R_L = f_L(1)/f_L(2)$ to be less than about 30% ($\Delta \log R_L \lesssim 0.15$).

In Figure 1 we compare the different measurements. Generally good agreement is found. In a few cases deviations of up to ± 0.2 dex are found which can be traced back to better, well exposed spectra being available now. Some stars appear to have time variable fluxes. We want to point out that we compare surface fluxes. Differences in the determination of angular radii also appear in this comparison while they cancel out when we determine element abundance ratios. We generally used the Barnes-Evans (1976) method to determine angular radii and surface fluxes.

III. Method of Abundance Determinations from Observed Emission Line Surface Fluxes

Element abundances can generally be expected to correlate with emission line fluxes, which can therefore be used to determine element abundances provided that the excitation processes are understood.

In the transition layers we find for optically thin lines and for collisional excitation and radiative deexcitation that the surface emission line flux F_L is given by

$$F_L = E_x(T)\ E_m(T)\ N_{el}/N_H \qquad (1)$$

Here $E_m(T)$ is the emission measure, defined as

$$E_m(t) = \int_{\Delta h} n_e^2\, dh = \int_{\Delta \ln T} n_e^2 (dh/d\ln T) d\ln T\,, \qquad (2)$$

where the integral has to be extended over the line forming layer, which usually corresponds to a layer over which the temperature changes by about a factor of 2 or $\Delta \ln T = 0.7$. (See for instance Pottasch 1963). The $E_x(T)$ in equation (1) describe the collisional excitation rates and depend on the collisional cross sections which are different for different lines. The factor N_{el}/N_H in equation (1) describes the element abundance for the line under investigation. For a measured surface flux F_L we can thus determine the product of $E_m(T)$ and the element abundance if the collisional cross sections are known. Since for different lines originating in the same temperature range the emission measures have to be the same, we can determine the relative abundances of these different chemical elements. If the different lines studied do not originate at the same temperature but at different temperatures, we must still require that the derived emission measures are a smooth function of the temperature. We can thus interpolate between the known emission measures.

For the Si IV lines at 1400 Å the commonly used $E_x(T)$ (Brown and Jordan 1981) were corrected by a factor of 3.16 because otherwise the Si IV emission measures always come out too high, which would indicate a higher Si abundance. On the other hand the emission measures derived for Si III often come out too low requiring a lower Si abundance. The conclusion is (see Hartmann *et al.* 1985) that something is wrong with the $E_x(T)$ for the Si IV lines. We have determined an empirical correction using the Si IV emission lines of main sequence stars for which the abundances are supposedly solar. This yielded a correction factor $\Delta \log E_m(\mathrm{Si\,IV}) = -0.5$. This correction has no influence on the N/C abundance ratios determined here. It also has no influence on the discussion of silicon abundance changes because we always compare with main sequence abundances.

In Figures 2a and 2b we have plotted the emission measures as a function of temperature T for the line forming region for several main sequence stars studied by Ayres *et al.* (1981) and for some luminosity class IV stars using solar abundances.* For all these stars the temperature dependence of the emission measures can be well represented by the relation $E_m \propto T^{-1.2}$ with the deviations usually being $\Delta \log E_m < 0.1$. Some deviations are most likely due to measuring uncertainties for the emission line fluxes which are estimated to be of the order of 15 to 25% (*i.e.*, 0.06 to 0.1 dex) and may occasionally be larger for faint lines.

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* We used: $\log N/C_\odot = 0.5$ and $\log \frac{C}{Si_\odot} = 0.85$ in close agreement with abundances determined by Anders and Grevesse (1989).

A theoretical interpretation for the simple relation $F_m \propto T^{-\gamma}$ was given by us (Böhm-Vitense 1987). The exponent γ can be determined from the ratio of the C II to C IV line emission measures. If, assuming solar abundance, the emission measure for the Si IV or N V lines appear too large to be consistent with this relation, the increased line strength can be attributed to an increased abundance of these elements. If the line is too weak, the abundance must be lower than solar.

In Figures 3a and b we have plotted the emission measures obtained for some giants and supergiants assuming the same solar abundances as used in Figure 2, namely log C = 8.5 and log N = 8.0 as well as log Si = 7.65 on the scale of log H = 12. In Figure 3a we see that for these giants the ratio of the C II to C IV line fluxes could also be represented by the relation $E_m \propto T^{-1.2}$, though a somewhat smaller exponent fits better for the supergiants. In any case it is quite obvious that the points for the NV emission measures are too high for all these giants and supergiants. The NV line flux is too large in comparison with the C lines. This indicates a larger nitrogen abundance. The apparent increase in log E_m for the NV lines as compared to those for the C lines immediately tells us the actual increase in log (N/C). It can be read off directly from the plots (see Figure 3) and comes out to be Δlog(N/C) = 0.6 and 0.5 for α Aqr and β Aqr respectively, as shown by the length of the arrows in Figure 3b. For β Cet and β Dra we find Δ log N/C = 1.10 and 0.24 respectively. For ϵ Vir a value of 0.6 is found for Δ log N/C. Considering the uncertainty in the emission line flux measurements and in d log E_m/d log T we estimate the uncertainty of the Δ log N/C to be generally < 0.27 dex (see Chapter IV).

In Figures 3 we also see an apparent enhancement of the Si IV emission measures as compared to the C emission measures, indicating an apparent increase in the Si/C abundance ratio. From nuclear reactions we do not expect an increase in the Si abundances due to the CNO cycle but we do expect a decrease in the C abundance due to the conversion of ^{12}C to

^{14}N. In this process we expect $^{14}N + ^{12}C$ to remain constant. This leads to the relation

$$N/C = \frac{N_\odot}{C_\odot} \frac{1 - \frac{\Delta C}{C_\odot} \cdot \frac{C_\odot}{N_\odot}}{1 + \frac{\Delta C}{C_\odot}} \tag{3}$$

where $\Delta C = -\Delta N$ and where N, C, ΔC and ΔN stand for the number of particles per unit volume. ΔC stands for the number of carbon nuclei which were converted into nitrogen. Equation (3) is an equation to calculate $\Delta C/C_\odot$ and thereby ΔC. For the solar abundances given above and for $N/C = 4\ N_\odot/C_\odot$ as determined above for α Aqr we find $\Delta \log C = -0.27 = \Delta \log (Si/C)$ for α Aqr in very good agreement with the apparent enhancement of the emission measures for Si relative to carbon as seen in Figure 3. It is the apparent increase in the Si IV emission measures also seen for the other stars in Figures 3 which confirms that N/C is enhanced for these stars by a factor of about 3.

For γ Tau the ratio of the C IV to C II emission line fluxes appears to be variable, it is always rather large (see Figure 4). This may possibly be related to the presence of a companion or to large active regions on the stellar surface with large CIV/CII line flux ratios. Flares may also be important. Reducing the C IV line flux to the usual C IV over C II line flux ratio could increase the overabundance of N/C by about 0.2 dex, the estimated uncertainty of our abundances determinations. This would bring the transition layer abundance ratio into better agreement with the photospheric abundance determinations for this stars. A similar though smaller effect is also seen for θ^1 Tau.

In Figure 5 we compare our results with photospheric abundance determinations by other authors. The agreement is as good as may be expected given the uncertainties of ± 0.2 dex estimated by all authors. If photospheric abundances have been determined by several authors the transition layer abundances correspond rather well to the averages of the photospheric abundances.

From the very meager statistics there is a suggestion that for the supergiants the transition layer abundance ratios may come out somewhat lower than the photospheric ones.

The photospheric determinations are based on NLTE analysis of the N I lines. Perhaps we might also have to consider NLTE temperature stratification for these supergiants for an even more accurate abundance determination. The transition layer value for α and β Aqr correspond better to theoretical expectations. But this must not mean that they are more correct. For β Aqr the C IV to C II line flux ratio is rather high, but not so for α Aqr. We realize, however, that even for these two supergiants the agreement between the different abundance determinations is still within less than ± 0.2 dex, the uncertainty estimate for these kinds of analyses. For β Dra the discrepancy is especially large. This star is situated right at the Linsky-Haisch boundary line. The NV line may possibly be weakened due to the lack of high enough temperatures in its transition layer. In Table 4 we give the data used in Figure 5.

From Figure 5 it appears that our method of N/C abundance determination from transition layer lines is as accurate as photospheric abundance determinations. It is much simpler and provides at the same time also the ratio of the carbon abundance relative to Si though the excitation of the Si IV lines may not be very well understood. The transition layer abundances are rather easy to study for a large number of stars and can also be obtained for F and G stars.

It can easily be shown that we do not even have to determine emission measures but can directly use the measured fluxes, because only line flux ratios are used in the analysis.

Unfortunately we cannot extend our studies to stars cooler than the Linsky Haisch boundary line for chromospheric emission, because no C IV and N V lines can be seen anymore. The very cool and very luminous stars cannot be analyzed in this way.

IV. Error Estimate

For well exposed spectra and reasonably strong emission lines the uncertainty in the flux measurements for each line are less or about 25% or roughly 0.1 dex as verified by the comparison of measurements by different authors. For underexposed spectra or very weak emission lines the errors may be twice as large. In this study we generally did not use underexposed spectra. We therefore estimate that for the stars studied the uncertainty in the line flux ratio of the C II and C IV line is 0.2 dex. For weak N V lines the uncertainty may in some cases be larger.

In order to determine the emission measure expected for the temperature where the NV lines are formed we have to extrapolate the emission measure line from log T = 5.00 to log T = 5.176. In the worst case the flux measurement errors for the two lines could be in the opposite sense. In this case the error in the gradient dlog Em/dlog T would be 0.382 and the error in the extrapolated Em for log T= 5.176 would be ± 0.07 dex in addition to the error in the C IV line flux leading to an error of ± 0.17 dex in the expected emission measure for the NV line and correspondingly in the nitrogen to carbon abundance ratio.

In the other extreme the measuring errors for both lines could be in the same sense. The gradient would then be correct and the error in the extrapolated Em would be 0.1 dex leading to an error in the N/C ratio of 0.1 dex.

In addition we now have to consider the error in the NV line flux. If this is also 25% as for the carbon lines then the *maximum error in the N/C ratio could be 0.27 dex* if all errors add up which in general they will not. The *more likely error would be the square root of the sum of the errors squared which is 0.22 dex.* For most of the giants studied here this error estimate should hold. The NV line is however frequently weaker than the carbon lines especially in stars in which nitrogen is not overabundant. In special cases the measuring error for the NV lines can be as high as 50% or 0.2 dex. For these exceptional stars with very weak NV lines the error could in the worst case increase to 0.37 dex if all errors would add up which of course in general they will not. For stars with very weak NV lines an *error of 0.37 dex would be an upper* limit for the error in the N/C abundance ratios.

Stars with normal nitrogen abundances are found in the F and early G star region where surface fluxes are generally large. For the cooler stars surface line fluxes are generally smaller but nitrogen is overabundant in the giants. For the giants we therefore find generally NV lines which on well exposed spectra can be measured with an accuracy of 25%. We therefore think that generally the upper limit for the errors discussed so far is about 0.27 dex. Exceptional cases are mentioned in the text.

Are there other uncertainties to be considered? A. Brown kindly pointed out to us that the C II lines form at lower temperatures than considered here. It appears to us that this must depend on the relation between electron density and temperature in those lower temperature regions. It will only be the case if the lower temperature regions have much higher electron densities or are much more extended. If the C II lines do indeed form at lower temperatures than assumed here then the Em(C II) will be larger. This will increase the gradient dlog Em/dlog T. This presumably would be nearly the same for all stars. The emission measures for log T = 5.176, the temperature where the NV lines form, will then be higher for all stars including the standard stars. Since we only determine excess abundance ratios as compared to the standard main sequence stars this does not affect our abundance ratio determinations. This would be of importance if we wanted to determine absolute abundances. In that case errors in the collisional excitation rates would also enter. For the determination of excess abundance ratios all these factors do not enter as long as all stars studied here are affected in the same way.

If the formation temperature for the C II lines should change along the giant sequence then this could influence the abundance results. If for instance log T should change by −0.1 the required Em would increase approximately by 0.5 dex. The Em(T) gradient would become steeper than assumed and the N/C abundance would have to be higher by about 0.1 dex. We see however at present no reason for such a change of the C II line forming temperature along the giant sequence.

The Si IV lines are sometimes hard to measure. They form, however, at temperatures intermediate between the C II and C IV lines. The excess abundance ratio of Si/C is therefore essentially independent of the adopted emission measure gradient. The uncertainty in the line flux measurement enters full. For this abundance ratio we therefore estimate the upper limit for the error to be generally 0.2 dex but for some stars might be as high as 0.3 dex. Any changes in the excitation rates along the giant sequence in addition to the dependence on the electron density could, however, introduce additional errors.

Figure 5 confirms our error estimates when considering that the photospheric abundance determinations also have an uncertainty of 0.2 dex at least.

V. Carbon, Nitrogen and Silicon Abundances for Giants Observed with IUE

A. The Data

In Table 5 we have collected the abundance ratios for N, C and Si as determined here for the giants. The abundance ratios log Si/C_{ms} were corrected for the reduced carbon abundances. They were determined from the measured values Δlog Si/C according to

$$\Delta \log Si/C_{ms} = \Delta \log Si/C + \Delta \log C \tag{4}$$

where $\Delta \log C < O$ and was calculated according to equation (3). The $\Delta \log Si/C_{ms}$ thus measure the apparent increase in silicon abundance as compared to the main sequence value.

B. The Temperature Dependence of the N/C Abundance Ratio

In Figure 6a we have plotted the Δ log N/C for the giants as a function of effective temperature, as determined from the B-V colors (Bōhm-Vitense 1981; Flower 1977) (interstellar reddening does not seem to be important for these bright stars as we checked from their two color plots). We see an increase in the average N/C ratio at B-V $\sim$ 0.8 or $\log T_{eff} = 3.73$ with a fairly large scatter. Some of the scatter is certainly observational. The maximum N/C ratios found here confirm the unexpectedly large admixture of CNO processed material for these stars. According to the calculations by Sweigart, Greggio and Renzini (1989) an increase of $\Delta \log \frac{N}{C} = 0.55$ is expected for the cool giants, *i.e.*, for log T ~ 3.72, depending somewhat on the mass of the stars.

Surprisingly we also find some F giants with an enhanced nitrogen abundance. The enhancement is up to twice the estimated error limit. No such large deviations to the negative side are found except for β Cas which is a δ Scuti star and the emission line fluxes may perhaps be caused by the pulsation rather than by an equilibrium transition layer.

Further studies are necessary to clarify the problem of the apparent increases in the N/C abundance ratios in the F giants.

C. Dependence of Deep Mixing on Rotational Velocities

In Figure 6b we have reproduced the data from Figure 6a for those stars for which rotational periods are known. We have indicated different period length by different symbols. Stars with large rotational velocities are generally found for B-V < 0.7. They have mostly low N/C ratios, though there are some exceptions. No correlation of N/C with rotational periods can be established for the stars with B-V < 0.7.

Large N/C ratios are found mainly for cooler stars with generally low v sin i. No dependence on rotation can be established for the cool stars either.

D. Dependence of Deep Mixing on Luminosity

In Table 6 we give the absolute magnitudes for the giants studied here, as determined by various methods, as explained in the table.

In Figure 6c we have plotted the N/C abundance ratios again as a function of T_{eff} but indicated different magnitudes by different symbols. No dependence of abundances on absolute magnitude is apparent for a given range of T_{eff}, at least not for the limited range in M_v covered by our program stars.

E. The Strength of the Si IV Lines

In Figure 7 we have plotted the derived Δ log N/Si. A general increase is observed as is to be expected for an increase in the nitrogen abundance. For some of the F giants we find, however, negative values, which if real, would mean either a decrease in nitrogen abundance, not verified by the N/C abundance ratio, or an increase in the silicon abundance which would be very surprising. Further studies are needed to clarify this problem. For several cool giants the increase in N/Si is not as large as expected for the increase in nitrogen abundance. The Si IV line strengths for these stars also appear to be enhanced. It remains to be studied whether this increase in the Si IV line strength is in fact due to an increase in the silicon to carbon abundance ratio, or whether it might be due to a blend with another line, perhaps the O IV forbidden line at 1401 Å. The line profiles on low resolution spectra suggest at most a small contribution from the O IV line. The available high resolution spectra for cool giants are either underexposed or do not show an additional line around 1400 Å, which could contribute.

In Figure 8 we have plotted the Δ log Si/C_{ms} abundance ratios as a function of T_{eff}. We again find apparently increased Si abundances by up to a factor of 2 for some F stars. They are preferentially stars with low v sin i. We wonder whether these stars might be descendents of Am or Ap stars as was suggested by T. Wheeler (1991), for these the surface abundances of carbon are decreased or the surface abundances of silicon increased supposedly due to diffusion. We also find apparently increased Si abundances for the cool giants with large N/C ratios indicating deep mixing. For these stars any surface abundance changes due to diffusion should be wiped out. Though the increases in Si IV line strength are not very large we do not think that all of them are just measuring uncertainties because we do not find a comparable number of negative Δ log Si/C_{ms}. We also find increased Si II (1808, 1816 Å) line strengths for many of the stars with increased Si IV line strengths. Clearly further studies are needed to clarify the excitation of the Si IV lines and also to determine photospheric abundances.

Helfer and Wallerstein (1968) determined Si/Fe ratios for several giants. The only star in common with our program stars is δ Boo A for which they find [Si/Fe] = 0.09 and [Fe/H] = −0.57, while we find here [Si/C] = 0.44. No C or N abundances could be determined by Helfer and Wallerstein.

Luck (1991) and McWilliams (1990) studied heavy element abundances in giants with $T_{eff} \lesssim 5500$ K. Luck finds generally a nitrogen to carbon abundance ratio in agreement with our determinations within the limits of error. His determinations indicate, however, a reduction in carbon abundance larger than expected from the increase in the N/C abundance ratio by about 0.25 dex in the average. Luck finds an increase in the Si/Fe abundance ratio by 0.23 dex in the average as compared to solar values. Comparing the silicon abundances to solar silicon abundances an increase of 0.1 dex is found in spite of the average lower Fe abundances as compared to the sun and in spite of the lower carbon abundances.

For the G and K giants (B-V > 0.7) we determine here an average increase in the silicon to carbon abundance ratio by 0.15 dex as compared to the main sequence F stars, which supposedly have solar abundances.

McWilliams does not give carbon or nitrogen abundances. From his data an average increase of the silicon to iron abundance ratio of 0.15 dex is found for the stars studied by us.

For the G and K giants the different studies thus seem to be in fair agreement.

It may nevertheless be interesting in this context to note that Feldman, Widing and Lund (1990) find increased Si IV, Si III and Si II transition layer line strengths in plage regions, which they interpret as an increased silicon abundance in those regions.

To clarify the problem of the silicon abundances in the transition layers photospheric silicon abundances need to be studied in F main sequence and giant stars studied here so we can compare abundance changes seen in the photospheres and in the transition layers.

F. Relation Between Nitrogen Enrichment and Lithium Abundances

In Table 5 we have also listed the lithium abundances determined by Brown *et al.* (1989), and Lambert, Dominy and Sivertsen (1980) and by Luck (1991). If the nitrogen enrichment is due to deep mixing we must expect also a destruction of lithium. In Figure 9 we compare the trends of the Li and N/C abundances. Comparing with the lithium abundance of log $\epsilon(\mathrm{Li}) \sim 3$ (if log $\epsilon(\mathrm{H}) = 12$) for the interstellar medium we find a reduction of $\epsilon(\mathrm{Li})$ by a factor of 4 for log $T_{\mathrm{eff}} = 3.74$ and by a factor of 100 for log $T_{\mathrm{eff}} \sim 3.70$, the temperature for which the nitrogen abundance starts to be generally high. A reduction of this order is according to Iben (1967) expected due to the mixing of the lithium rich surface layers with the lithium poor convection zones of increasing depths. For log $T_{\mathrm{eff}} = 3.7$ when nitrogen rich material has been mixed to the surface the convection zone reaches deep into the lithium burning region and further reduction in lithium abundances must be expected and seems to be indicated for log $T_{\mathrm{eff}} < 3.7$. It is still continuing with a timescale of about 10^5 years, a surprisingly long time after the nitrogen enrichment, when we expect very short timescales for the lithium burning at the bottom of the convection zones. It is not clear whether for such low temperatures we may see lower mass stars on the red giant branch or whether we are still dealing with the same mass range as for the higher temperature giants. If so then the slow decrease in $\epsilon(\mathrm{Li})$ must mean that the mixing of the surface material down to the lithium destruction layers is a rather slow process for these cool giants.

VI. Summary

We have shown that the Carbon to Nitrogen abundance ratios can be determined from the emission line fluxes of the C II, C IV and N V lines originating in the lower part of the transition regions between stellar chromospheres and coronae. For stars in common the abundances obtained in this way agree with those obtained from photospheric studies by Luck, Luck and Lambert, and Lambert and Ries within the quoted error limits of $\Delta\log \mathrm{N/C} \sim \pm 0.22$.

The abundance analysis by means of transition layer lines permits us to determine nitrogen and carbon abundances also for F and early G giants for which CN molecular bands cannot be analyzed. We can thus follow the evolution of the N/C abundance ratio along the giant branch. We find a general increase in the N/C ratio by roughly a factor of 3 to 6 for B-V $\gtrsim 0.8$. A factor of about 4 is expected theoretically (see Sweigart, Greggio and

Renzini 1989) for increasingly deeper mixing when the outer convection zone reaches deeper into the region where CNO processing has taken place earlier. The high degree of nitrogen enrichment in some stars is, however, surprising. Additional mixing appears to be required at least for some stars.

The analysis also seems to indicate an increasing silicon enrichment for most cool giants. It remains to be seen whether this is real. So far we have not found any reason to explain the strengths of the Si IV lines other than by increased abundances. If so, the reason for this remains obscure. The excitation of the Si IV lines may not yet be well understood.

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Table 1
Measured Fluxes at Earth
(erg cm^{-2} s^{-1})

STAR	B - V	log T_{eff}(K)[a]	SPECTRAL TYPE	f_L(C II)[b]	f_L(C IV)[b]	f_L(Si IV)[b]	f_L(N V)[b]	v sin i	Remarks
ο Gem	0.40	3.837	F3 III	3.0(-13)	5.2(-13)	1.7(-13)	5.8(-14)	90.[c]	
25 Mon	0.44	3.825	F6 III	2.7(-13)	3.2(-13)	1.5(-13)	4.2(-14)	25.[c]	var?, Hyades group
ι Vir	0.52	3.802	F6 III	4.3(-13)	5.4(-13)	2.0(-13)	7.1(-14)	16.[c]	var, 4.06 - 4.11 V
31 Com	0.67	3.759	G0 IIIp	7.1(-13)	1.5(-12)	7.2(-13)	2.3(-13)	77.[d]	Hertz.gap, cluster member
35 Cnc	0.68	3.756	G0 III	1.3(-13)	2.5(-13)	7.7(-14)	7.8(-14)	90.[c]	NGC 2632, RV var.
ψ^3 Psc	0.69	3.753	G0 III	3.3(-13)	6.8(-13)	3.5(-13)	1.0(-13)	97.[c]	RV var?
24 UMa	0.77	3.732	G4 III-IV	1.8(-13)	2.0(-13)	2.1(-14)	1.2(-13)	<17[d]	var, amp .058 V, .9 d
HR 9024	0.79	3.726	G1 IIIe	1.2(-13)	3.6(-13)	1.8(-13)	3.3(-13)	20.[c]	overactive
δ CrB	0.80	3.724	G3.5 III-IV	2.2(-13)	3.3(-13)	1.2(-13)	7.3(-14)	<17[d]	
ε UMi	0.89	3.701	G5 III	4.0(-13)	9.9(-13)	8.4(-13)	5.7(-13)	23.[c]	SB, var, P=39 d, RS CVn
γ Hya	0.92	3.692	G8 IIIa	5.0(-14)	8.7(-14)	4.2(-14)	6.2(-14)	<17[d]	Sirius group, RV var.?
ε Vir	0.94	3.687	G8 IIIab	6.6(-14)	8.6(-14)	1.0(-13)	5.1(-14)	2.7[c]	var?, prob. Hyades gr.
β Her	0.94	3.687	G7 IIIa	8.7(-14)	1.7(-13)	1.0(-13)	5.1(-14)	3.4[c]	SB, P=411 d, var?
θ^1 Tau	0.95	3.685	K0 IIIb Fe-0.5	1.9(-13)	1.6(-13)	2.0(-13)	8.7(-14)	3.4[c]	SB, P≈3000 d
δ Boo	0.95	3.685	G8 III CN-1	3.2(-14)	4.6(-14)	1.0(-13)	1.6(-14)	<19[d]	SB, var?
γ Tau	0.99	3.675	K0 IIIab CN1	7.8(-14)	1.4(-13)	1.5(-13)	6.2(-14)	2.4[c]	SB, amp var .3 V
β Gem	1.00	3.672	K0 IIIb	1.2(-13)	1.4(-13)	2.5(-13)	1.0(-13)	1.9[c]	var?
ε Tau	1.01	3.670	G9.5 III CN 0.5	4.0(-14)	2.7(-14)	7.4(-14)	2.7(-14)	3.0[c]	double
β Cet	1.02	3.667	K0 III CH-IH,K-.51	4.7(-13)	4.5(-13)	8.9(-13)	7.0(-13)	3.2[c]	var?

[a] The effective temperatures are taken from Böhm-Vitense (1981) and Flower (1977) for giants with B - V < 0.9.
[b] The fluxes have units of erg cm^{-2} s^{-1}. The numbers in parentheses are powers of ten.
[c] from Rutten (1987)
[d] from Hoffleit and Jaschek (1982)

Table 2
Angular Radii and log of Surface Fluxes

STAR	SPECTRAL TYPE	θ^a	θ^b	θ^c	$F_L(C\ II)^d$	$F_L(C\ IV)^d$	$F_L(Si\ IV)^d$	$F_L(N\ V)^d$
o Gem	F3 III	0.32	----	0.30	5.11	5.35	4.86	4.54
25 Mon	F6 III	0.30	----	0.29	5.09	5.18	5.07	4.29
ι Vir	F6 III	0.55	----	0.52	4.78	4.88	4.49	4.03
31 Com	G0 IIIp	0.47	----	0.45	5.14	5.46	5.15	4.64
35 Cnc	G0 III	0.22	----	0.21	5.05	5.33	4.82	4.82
ψ^3 Psc	G0 III	0.36	----	0.35	5.02	5.34	5.05	4.51
24 UMa	G4 III-IV	0.65	----	0.63	4.25	4.30	4.32	4.08
HR 9024	G1 IIIe	0.36	----	0.35	4.57	5.06	4.77	5.03
δ CrB	G3.5 III-IV	0.66	----	0.64	4.33	4.51	4.07	3.85
ε UMi	G5 III	0.91	1.02	0.89	4.31	4.71	4.62	4.47
γ Hya	G8 IIIa	1.68	1.80	1.65	2.88	3.12	2.80	2.97
ε Vir	G8 IIIab	1.87	1.88	1.85	2.90	3.02	3.08	2.79
β Her	G7 IIIa	1.92	2.00	1.90	3.00	3.29	3.06	2.77
θ^1 Tau	K0 IIIb Fe-0.5	1.19	1.22	1.18	3.75	3.67	3.78	3.41
δ Boo	G8 III CN-1	1.42	1.56	1.40	2.83	2.99	3.15	2.54
γ Tau	K0 IIIab CN1	1.39	1.34	1.38	3.24	3.50	3.52	3.13
β Gem	K0 IIIb	4.47	4.47	4.45	2.41	2.47	2.73	2.35
ε Tau	G9.5 III CN 0.5	1.51	1.49	1.51	2.87	2.70	3.14	2.71
β Cet	K0 III CH-IH,K-.51	3.05	3.01	3.04	3.33	3.31	3.61	3.51

[a] Angular radii were calculated from the Barnes-Evans method for B-V. These values were used to calculate the surface fluxes. The units are 10^{-3} arc sec.

[b] Angular radii were calculated from the Barnes-Evans method for R-I. Values not listed are at or beyond the limit of accuracy for this color index.

[c] Angular radii were calculated from the apparent magnitude, the T_{eff}, and the bolometric correction.

[d] Log of surface fluxes are in unit of erg cm^{-2} s^{-1}.

Table 3
Surface Fluxes given by other Authors
and Remeasured in this Paper

STAR	F_L(C II)[a]	F_L(C IV)[a]	F_L(Si IV)[a]	F_L(N V)[a]	Reference
o Gem	5.12	5.30	5.01	4.58	c
25 Mon	5.10	5.30	5.05	4.36	c
ι Vir	4.51	4.68	4.49	3.92	d
31 Com	5.22	5.52	5.14	4.62	d
35 Cnc	5.08	5.45	5.11	4.97	c
ψ^3 Psc	4.89	5.36	----[b]	----[b]	c
24 UMa	4.44	4.42	4.51	4.18	d
HR 9024	4.74	5.14	----[b]	----[b]	c
ε Vir	3.08	3.20	2.97	2.82	d
β Her	3.18	3.30	3.00	2.88	d
θ^1 Tau	3.66	3.76	3.76	3.42	d
γ Tau	3.24	3.52	3.43	3.14	d
β Gem	2.49	2.67	2.87	2.40	d
ε Tau	3.08	2.89	3.15	3.20	d
β Cet	3.42	3.42	3.60	3.70	d

[a] log of surface fluxes are in unit of erg cm^{-2} s^{-1}.
[b] the line is measureable but was not given in this study.
[c] Simon and Drake 1989
[d] Oranje 1986

Table 4
Comparison of Abundance Ratios Determined from Transition Layer Lines
and Ratios Determined by Traditional Methods

Star	Δlog N/C[a]	Δlog N/C[b]	Δlog N/C[c]	Δlog N/C[d]	Δlog N/C[e]	Δlog N/C[f]	Δlog $N/C_{B.M}$[g].
ε Vir	0.86	----	----	0.70	----	0.44	0.62
γ Tau	0.72	----	----	0.60	0.74	0.17[h]	0.42
θ^1 Tau	0.61	----	----	----	----	----	0.68
β Gem	0.65	----	----	0.65	0.53	0.50	0.49
ε Tau	0.72	----	----	----	0.93	0.14[h]	0.87
β Cet	1.04	----	----	----	----	----	1.10
α Ari	0.55	----	----	----	0.25	----	0.54
θ Cen	0.59	----	----	----	----	----	0.82
δ Boo	----	0.32	----	0.20	----	0.56	0.37
ρ Cyg	----	0.65	----	----	----	----	0.91
η Her	----	0.54	----	----	----	0.74	0.65
β Dra	----	----	0.77	----	----	----	0.24
α Aqr	----	----	0.73	----	----	----	0.50
β Aqr	----	----	0.83	----	----	----	0.60

[a] Lambert and Ries (1981)
[b] Luck (1991)
[c] Luck and Lambert (1985)
[d] Cottrell and Sneden (1986)
[e] Gratton (1985)
[f] Kjaergaard *et al.* (1982)
[g] data from transition lines (see Figures 3 and 4).
[h] not plotted because value is so discordant with other determinations

Table 5
Excess Abundance Ratios as Compared to Solar Abundances
Determinations from our flux measurements

Star	B - V	Δlog N/C	Δlog N/Si	Δlog $Si/C_{m.s.}$ [a]	log ε(Li) [i]
o Gem	0.40	0.01	0.05	-0.06	----
25 Mon	0.44	-0.03	-0.31	0.29	----
ι Vir	0.52	0.02	0.01	0.01	----
31 Com	0.67	-0.06	-0.20	0.15	----
35 Cnc	0.68	0.30	0.35	-0.14	----
ψ^3 Psc	0.69	-0.06	-0.13	0.08	----
24 UMa	0.77	0.59	0.15	0.21	----
HR 9024	0.79	0.66	0.46	-0.07	----
δ CrB	0.80	0.17	0.20	-0.08	1.2[d]
ε UMi	0.89	0.50	0.12	0.20	----
γ Hya	0.92	0.66	0.55	-0.16	1.3[d]
ε Vir	0.94	0.62	0.16	0.21	0.09[e]
β Her	0.94	0.26	0.05	0.13	----
θ^1 Tau	0.95	0.68	0.23	0.17	0.86[e]
δ Boo	0.95	0.37	-0.19	0.44	0.8[d],0.9[e],0.85[f]
γ Tau	0.99	0.42	-0.03	0.31	0.7[d],1.11[e]
β Gem	1.00	0.49	0.06	0.25	0.6[d],0.44[e]
ε Tau	1.01	0.87	0.15	0.31	1.2[d],0.9[e]
β Cet	1.02	1.10	0.44	0.08	<0.2[d],<0.3[e]

Determinations from flux measurements of other Authors

Star	B - V	Δlog N/C	Δlog N/Si	Δlog $Si/C_{m.s.}$ [a]	log ε(Li) [i]
20 Peg[b]	0.34	0.35	-0.22	0.46	----
β Cas[c]	0.34	-0.37	-0.33	0.02	----
HR 1889[b]	0.43	0.33	0.00	0.22	----
45 Aur[b]	0.43	0.49	0.06	0.25	----
18 Com[b]	0.43	-0.04	-0.13	0.10	----
HR 8191[b]	0.47	0.28	0.15	0.04	----
α Aur Ab[g]	0.60	-0.08	-0.20	0.14	2.4[h]
ν Peg[c]	0.61	-0.19	-0.17	0.02	----
FK Com[c]	0.84	0.29	0.02	0.18	----
ρ Cyg[c]	0.89	0.91	0.43	0.05	0.9[d],0.97[f]
α Aur Aa[g]	0.90	0.17	-0.22	0.34	1.2[h]
10 LMi[c]	0.92	0.55	0.11	0.23	----
η Her[c]	0.92	0.65	0.23	0.16	0.9[d],0.93[f]
ξ Her[c]	0.94	0.66	0.30	0.09	1.3[d]
θ Cen[c]	1.01	0.82	0.23	0.22	-0.39[e]
λ And[c]	1.01	-0.08	-0.05	-0.01	----
12 Cam[c]	1.12	0.76	0.32	0.11	----
σ Gem[c]	1.12	0.72	0.45	-0.04	<0.3[d]
DK Dra[c]	1.14	0.46	0.23	0.07	----
α Ari[c]	1.15	0.54	-0.17	0.51	<0.0[d],<0.3[e]

[a] the carbon abundance has been adjusted to main sequence value.
[b] Simon and Drake 1989
[c] Oranje 1986
[d] Brown *et al.* 1989.
[e] Lambert *et al.* 1980.
[f] Luck 1991
[g] Ayres 1988
[h] Boesgaard 1971
[i] Only the first values are plotted in Figure 9. Other values are presented to show the range for the Lithium abundance determinations.

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Weiler. E. J. and Oegerle, W. R. 1979, *Ap. J. Suppl.*, **39**, 537.

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Captions

Figure 1. We compare our measurements of surface line fluxes with those of Oranje (1986) and Simon and Drake (1989).

Figure 2. The temperature dependence for the emission measures of solar abundance main sequence and luminosity class IV stars is shown in 2a and 2b, respectively. We generally find Em α $T^{-1.2\pm0.2}$ (solid lines).

Figure 3. When the temperature dependence for the emission measures is determined from the C II and C IV lines in giants and supergiants (dashed lines), excess emission measures for the Si IV and N V lines are found when solar abundances are assumed as seen in 3a and 3b, respectively. The apparent excess in the emission measures for the Si IV and N V lines is due to larger abundance ratios N/C and Si/C. The deviations from the $T^{-\gamma}$ relation (dashed lines) determined from the carbon lines give the abundance changes as shown in Figure 3a and 3b. This indicates a decrease in the carbon abundance and an increase in the nitrogen abundance. Solid lines are the best fit to the Em α $T^{-1.2}$ relation.

Figure 4. The transition layer emission measures are shown as a function of effective temperature for some stars which were also studied by Lambert and Ries (1981). Excess nitrogen abundances are also found from the transition layer lines.

Figure 5. The photospheric excess abundance ratios, as compared to solar abundance ratios of nitrogen to carbon, obtained by other authors, are compared with the ones found here from the transition layer lines. The limits of error for both our study and the traditional approach of the other studies are shown in the lower right corner. The diagonal solid line would be obtained for perfect agreement. All stars are giants except the open circles which are supergiants from the Luck and Lambert (1985) paper.

Figure 6a. The excess abundance ratios of nitrogen to carbon (as compared to solar abundances) are shown for giants as a function of effective temperature. The nitrogen to carbon ratio increases for cooler stars.

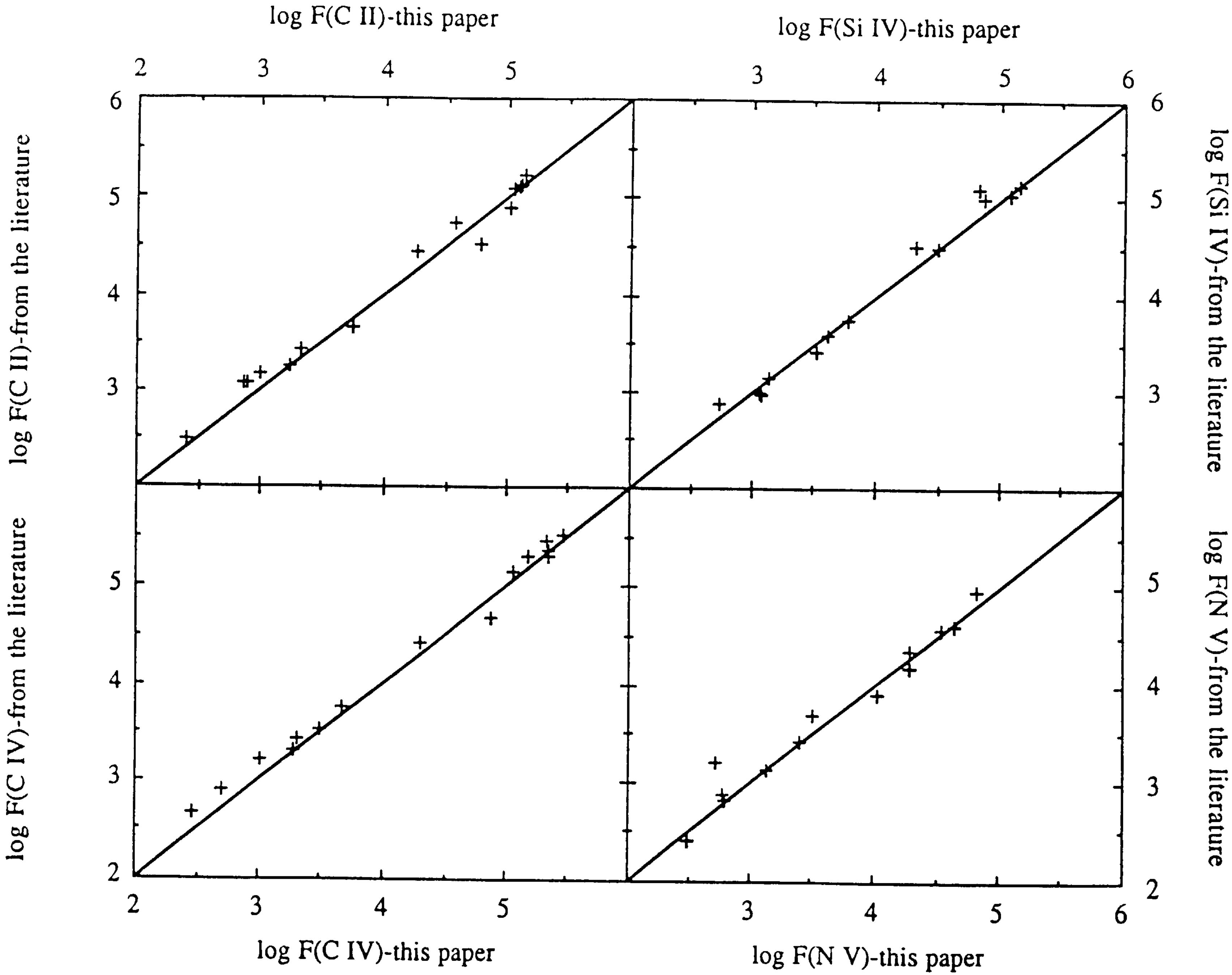
Figure 6b. Figure 6a is reproduced for stars with known rotational periods; different rotational periods are indicated by different symbols as explained in the Figure.

Figure 6c. Figure 6a is reproduced, but absolute visual magnitudes are indicated by different symbols.

Figure 7. The excess abundance ratios of nitrogen to silicon, as compared to the solar one, are plotted as a function of effective temperature.

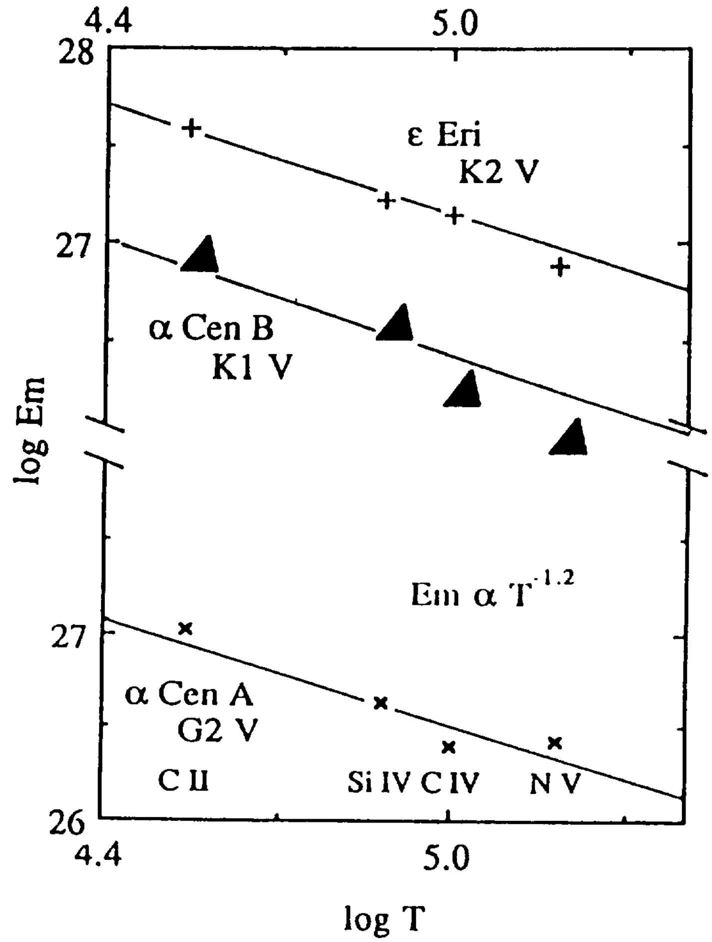
Figure 8. The abundance ratios of silicon to carbon (adjusted to main sequence carbon abundance, see text) as compared to the solar ones are shown as a function of effective temperature.

Figure 9. Lithium abundance and excess abundance ratios of nitrogen to carbon (as compared to solar abundances) are shown for the same sample of giants as a function of effective temperature.

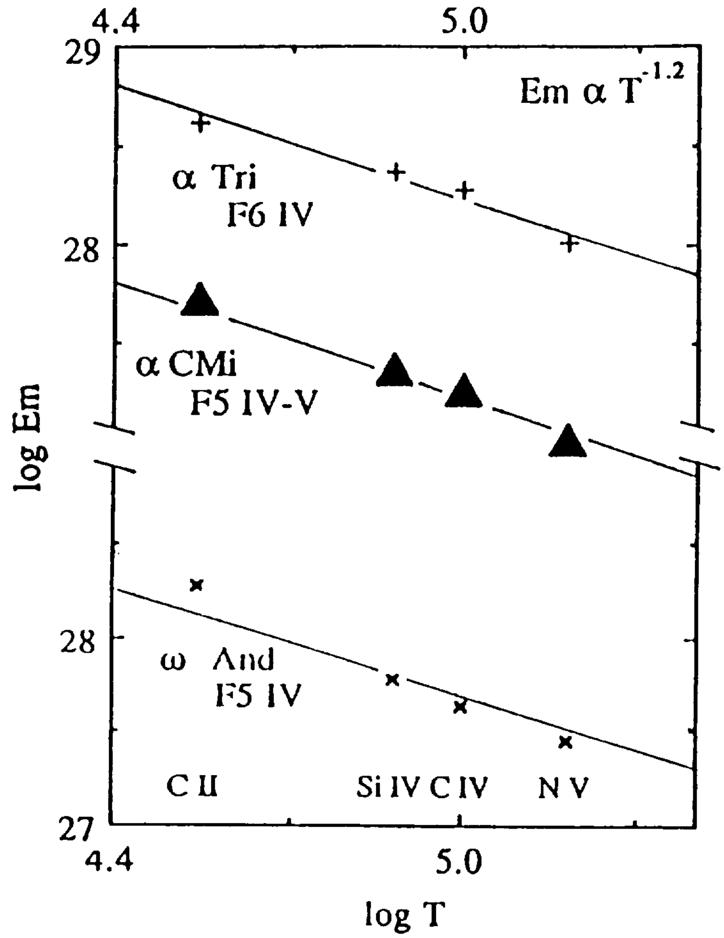


Böhm-Vitense and Mena-Werth

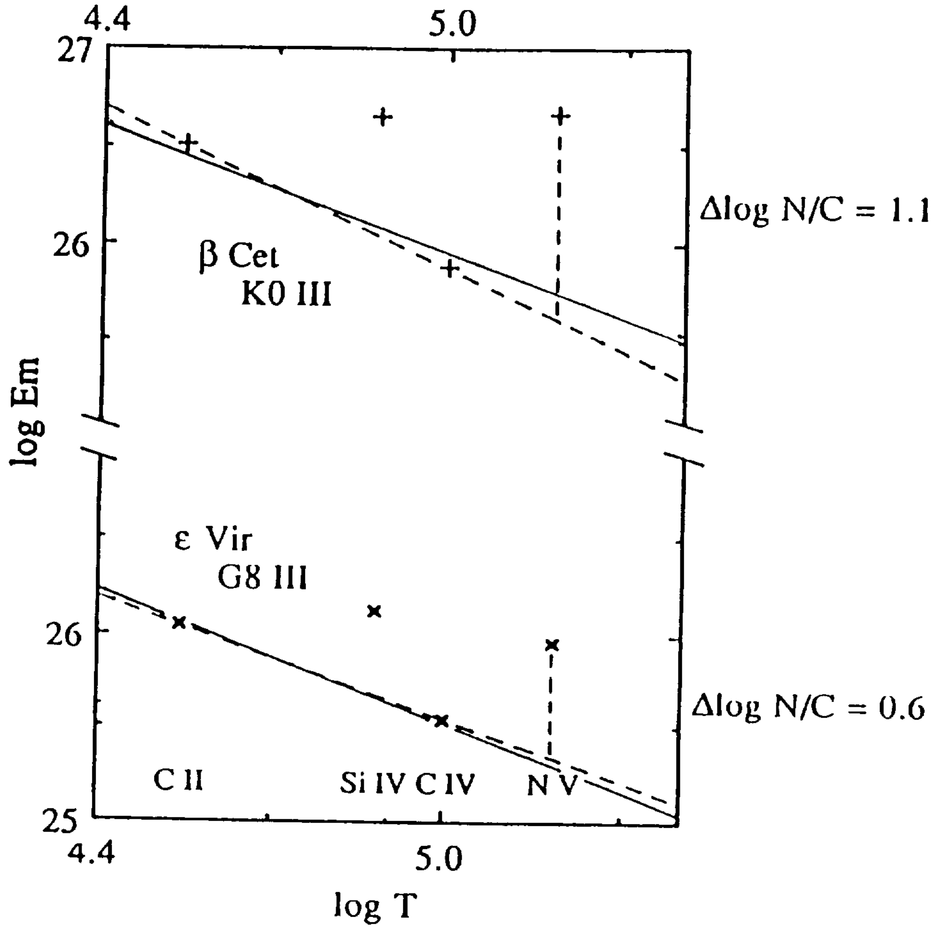
Figure 1



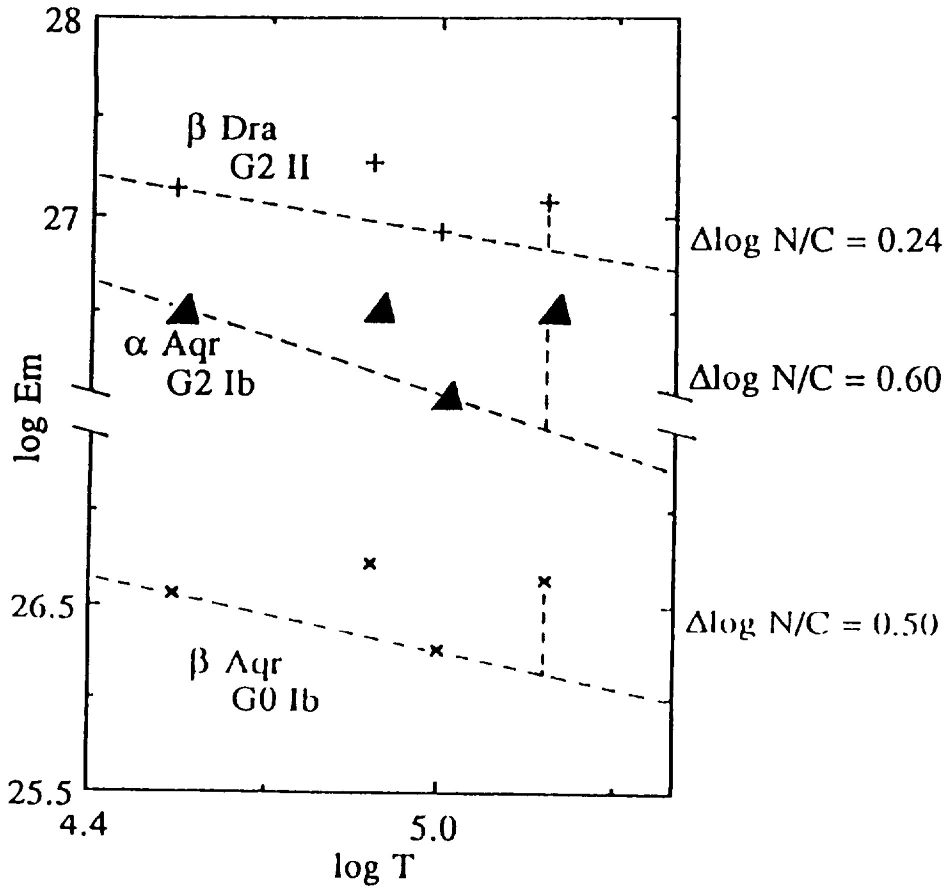
Böhm-Vitense and Mena-Werth Figure 2a



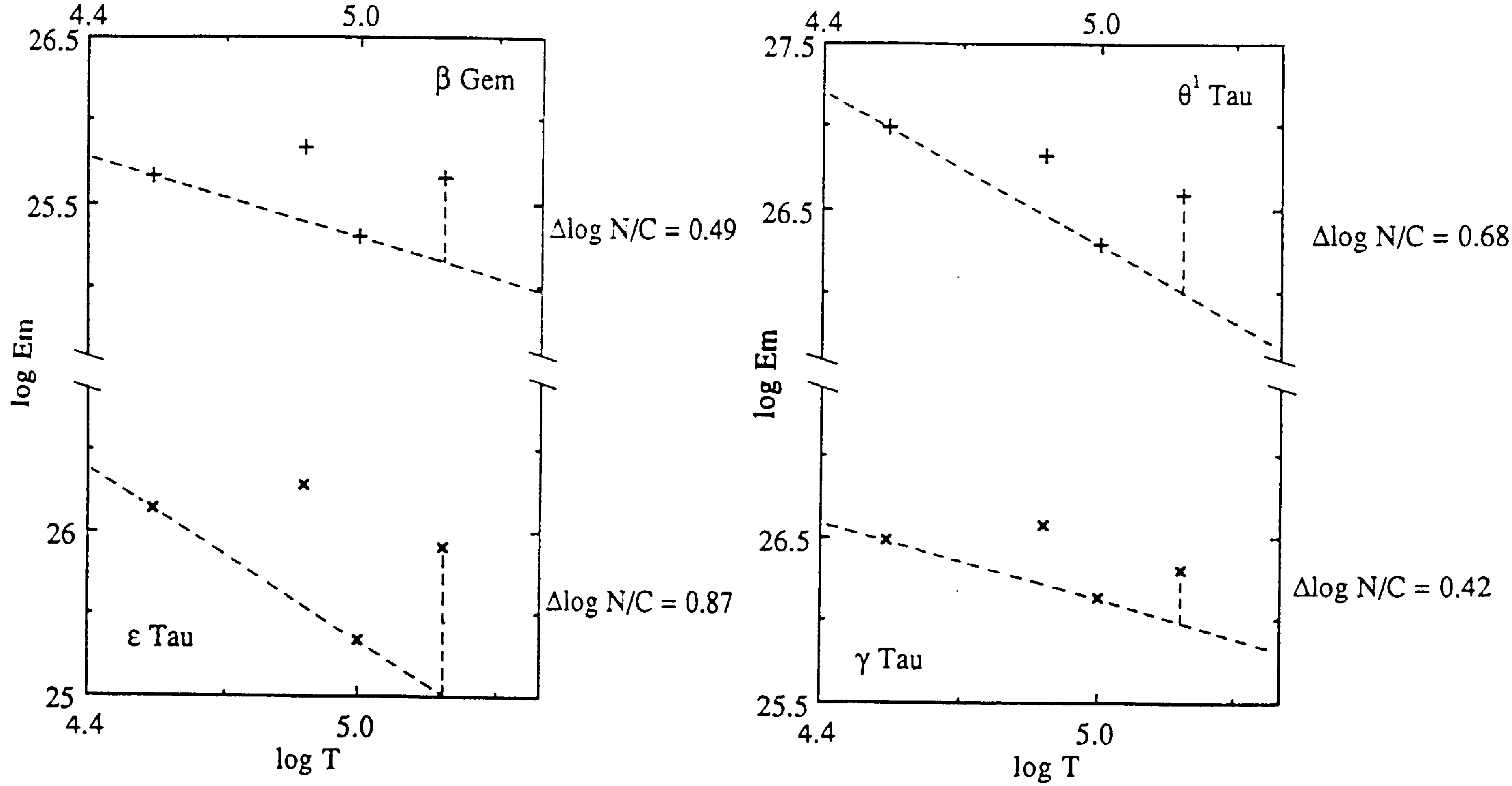
Böhm-Vitense and Mena-Werth Figure 2b



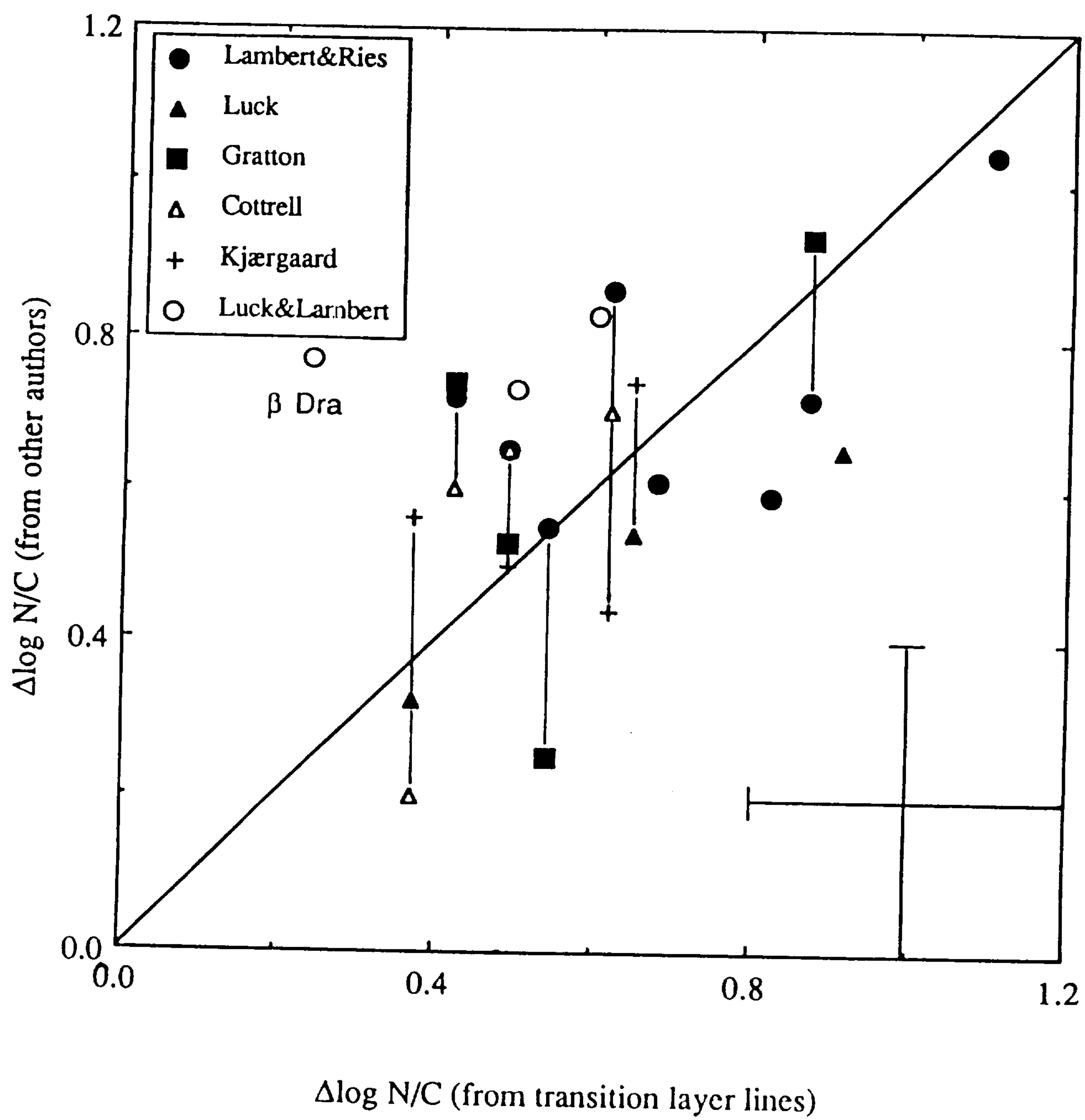
Böhm-Vitense and Mena-Werth Figure 3a



Böhm-Vitense and Mena-Werth Figure 3b

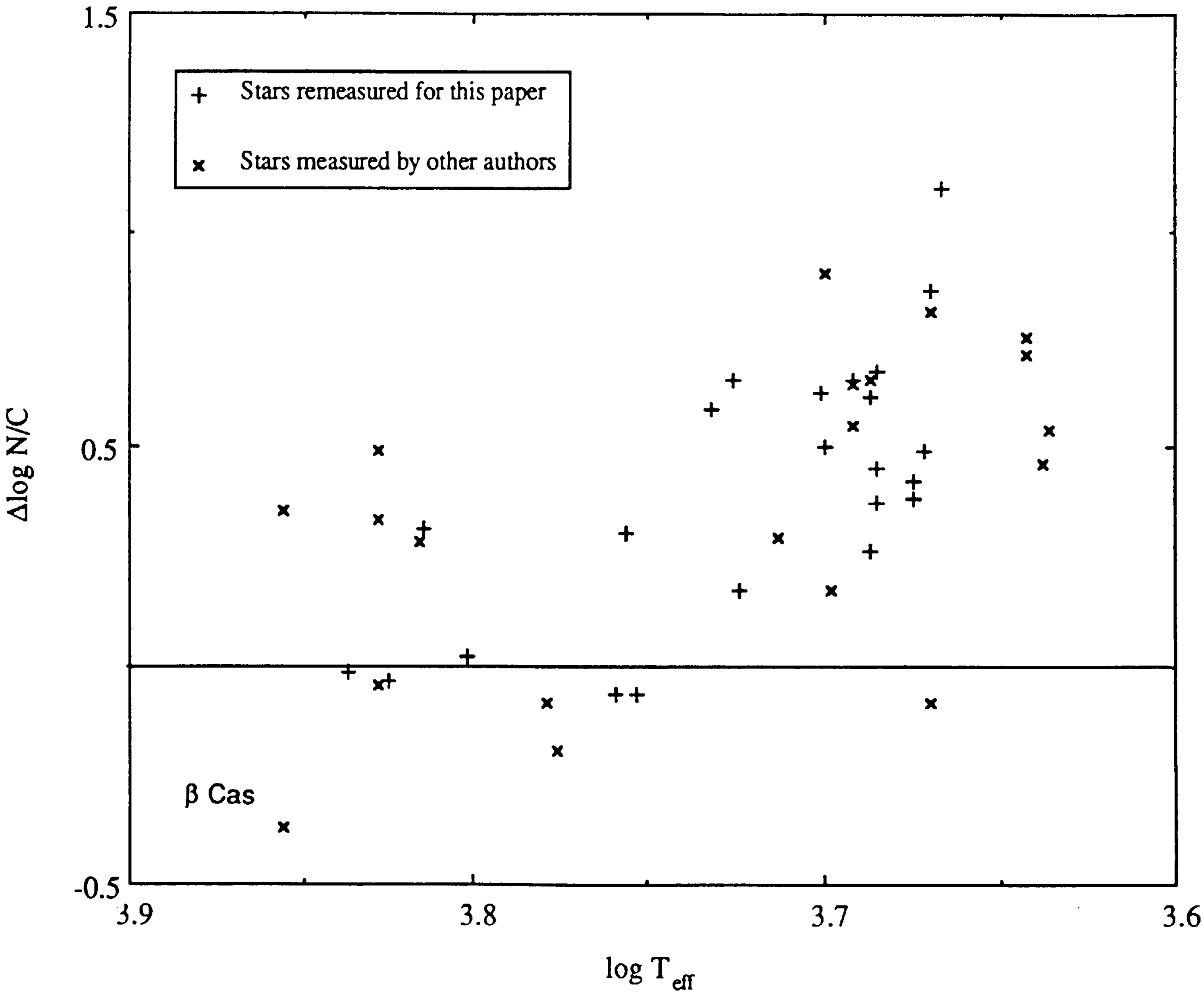


Böhm-Vitense and Mena-Werth Figure 4



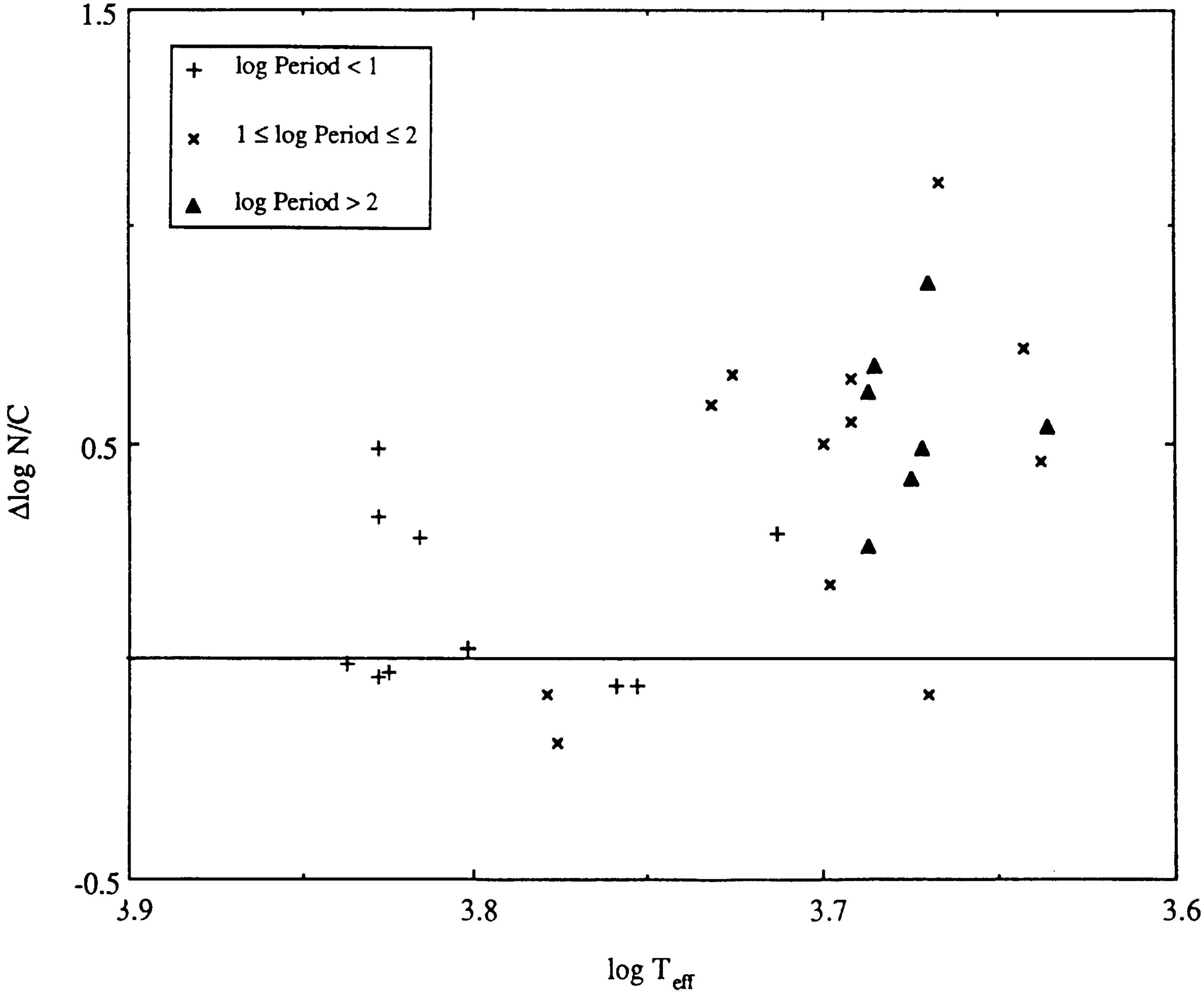
Böhm-Vitense and Mena-Werth

Figure 5



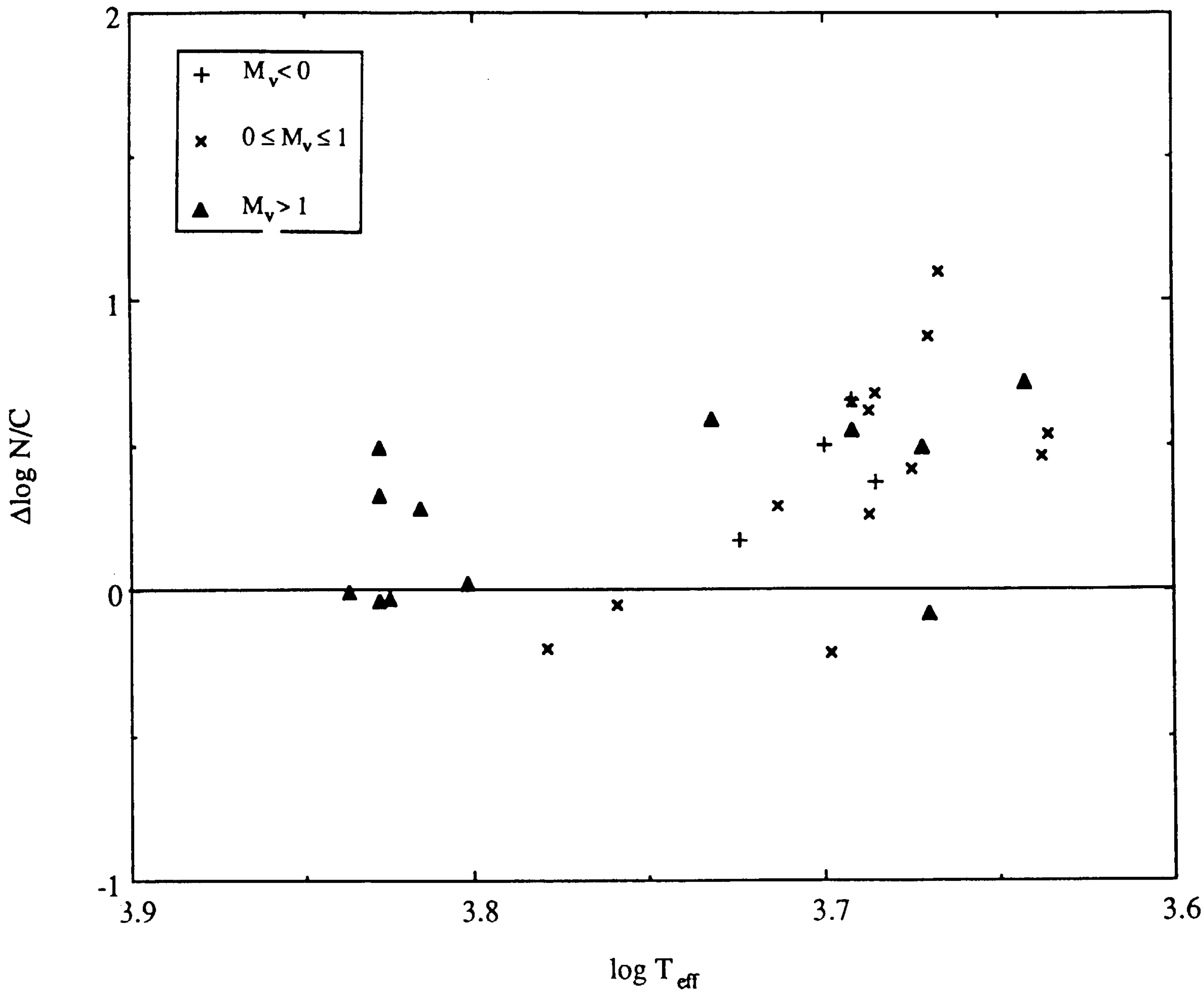
Böhm-Vitense and Mena-Werth

Figure 6a



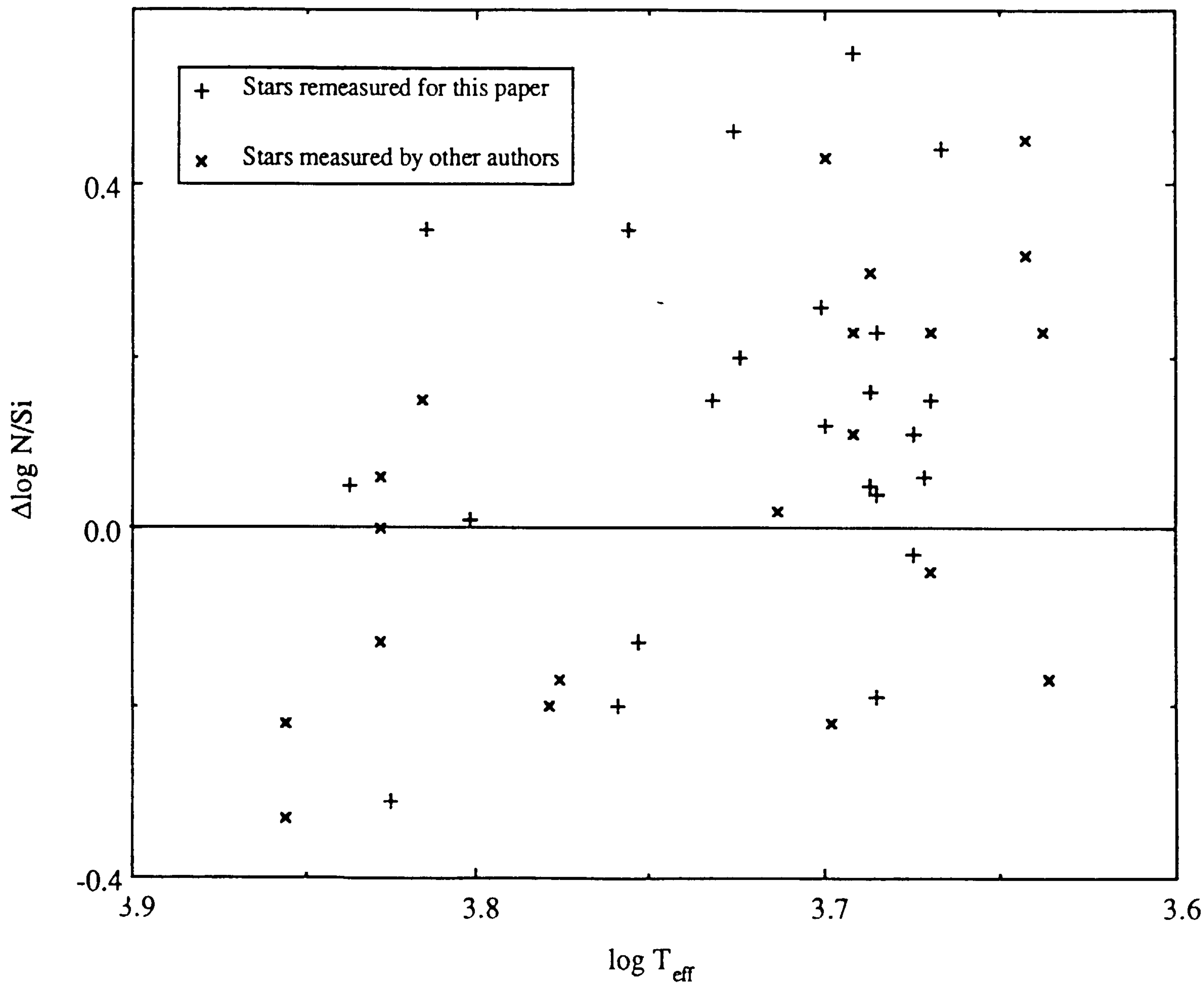
Böhm-Vitense and Mena-Werth

Figure 6b



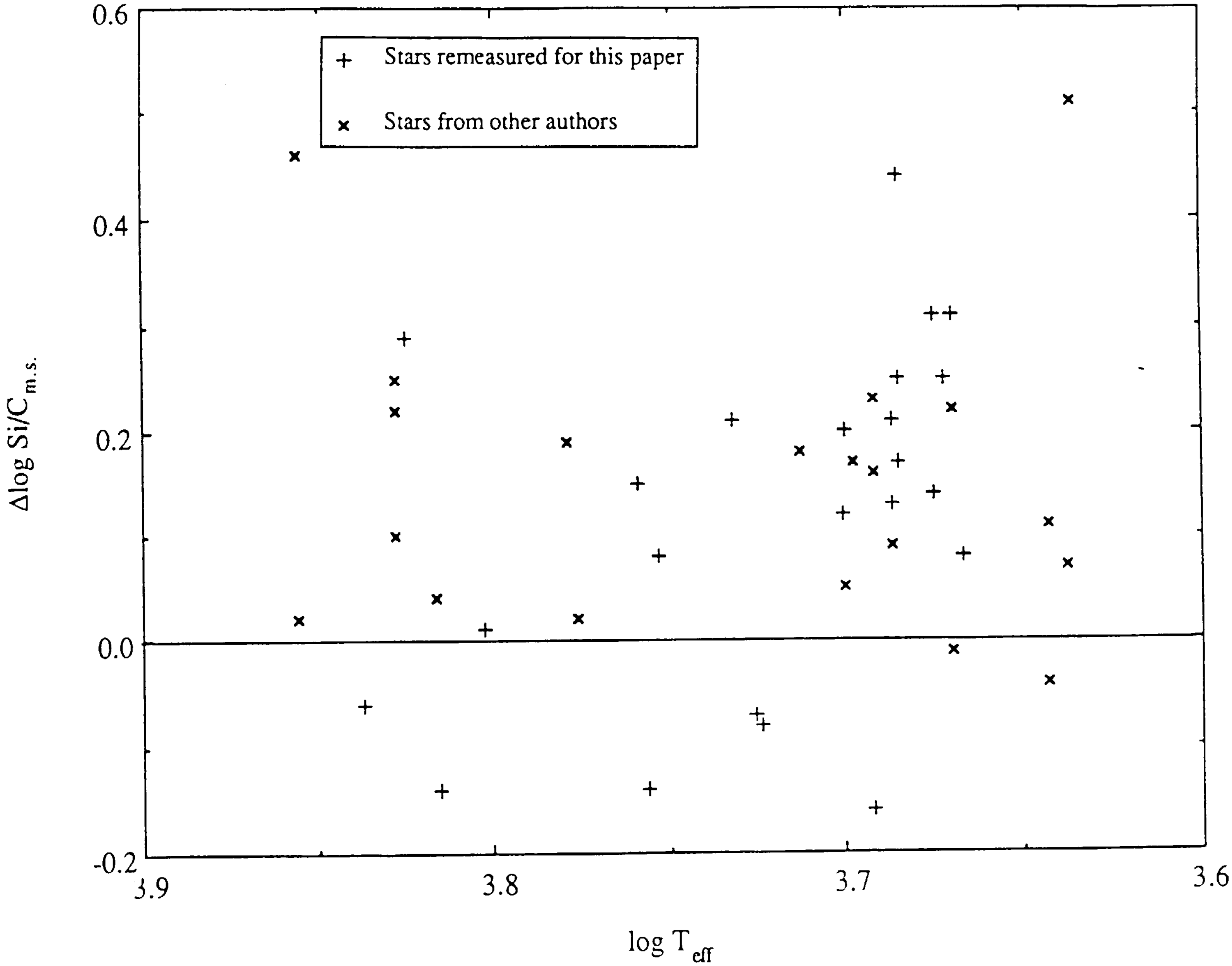
Böhm-Vitense and Mena-Werth

Figure 6c



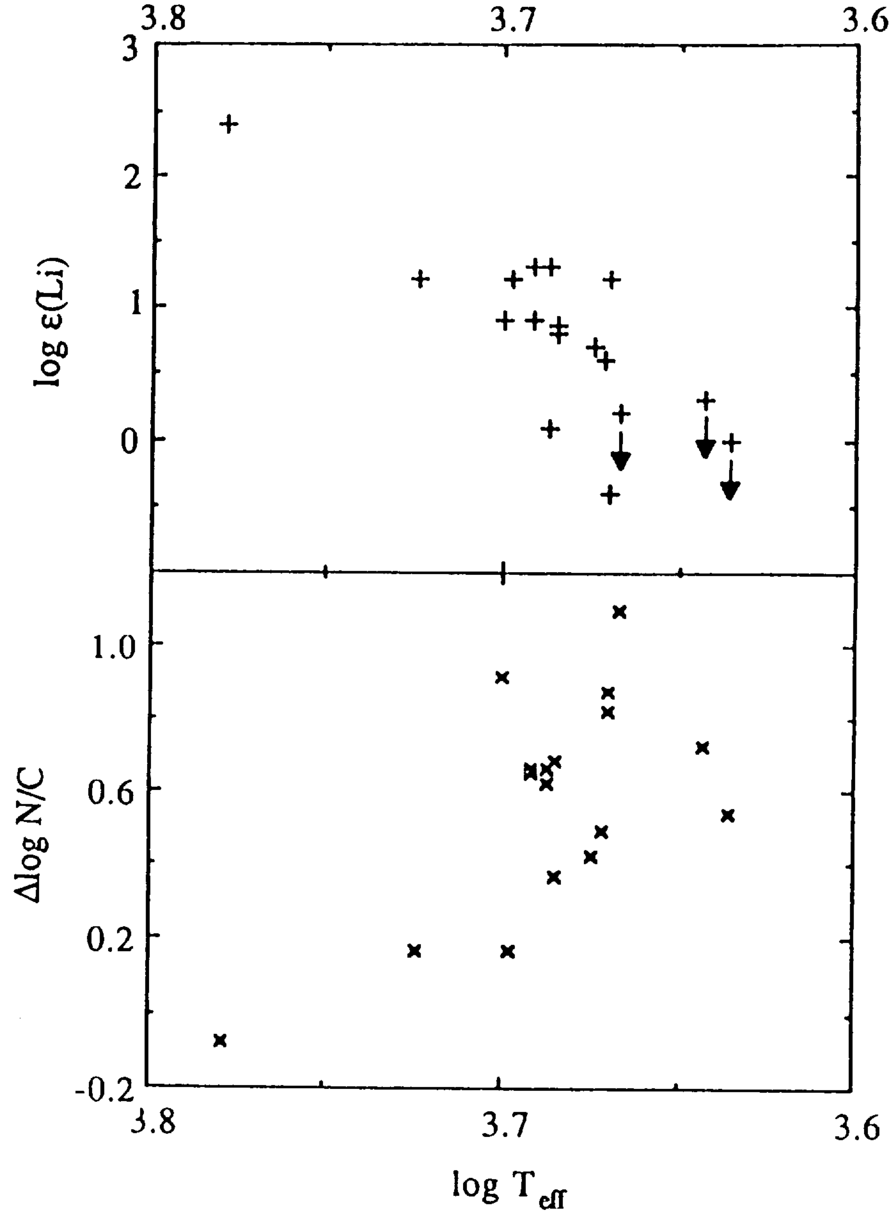
Böhm-Vitense and Mena-Werth

Figure 7



Böhm-Vitense and Mena-Werth

Figure 8



Böhm-Vitense and Mena-Werth Figure 9

Rotation and Transition Layer Emission in Cool Giants

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Abstract

Gray found that field giants with $T_{eff} \lesssim 5500$ K experience a steep decrease in rotational velocities coupled with a decrease in transition layer emission. He attributes this decrease to fast magnetic braking. Endal and Sofia and Gray and Endal find that it can also be explained by redistribution of angular momentum for rapidly increasing depths of the convection zones if these rotate with depth independent specific angular momentum.

We represent here additional arguments in favor of the latter interpretation: The increase of N/C abundances due to deep mixing occurs at the same point as the decrease in v sin i. On the other hand, the ratios of the CIV to CII emission line fluxes decrease at this point indicating smaller contributions of MHD wave heating. The X-ray fluxes decrease at nearly the same T_{eff}. We thus find no observations which would indicate larger magnetic activity which could lead to fast magnetic braking.

Theory predicts a rapid increase in the convection zone depth at the T_{eff} where the decrease in v sin i is observed. This can explain the observed phenomena.

1. Introduction

1.1. Rotational velocities

Gray (1981, 1982) pointed out that along the giant evolutionary sequence the rotational velocities v sin i appear to decrease abruptly around spectral types G5 to G8 III. This was later (1989) revised to a decrease at G0 III. Gray also pointed out in 1982 that correlated with this occurs a steep decrease in the C IV emission line fluxes at 1550 Å originating in the transition layers between stellar chromospheres and coronae. Simon and Drake (1989) state that they cannot confirm a steep decrease of v sin i at G5 III but instead see a smooth decline for stars later than G0 III. They explain their different conclusion by the fact that Gray did not consider upper limits for v sin i while they included them. Gray as well as Simon and Drake suggest that magneto-hydrodynamic braking due to stellar winds decreases the rotational velocities of the giants when they evolve to lower effective temperatures. On the other hand, Endal and Sofia (1978), and Gray and Endal (1982) point out that the expansion of the stars on the red giant branch together with the rearrangement of angular momentum due to the increasing depth of the convection zones may well explain the decrease of v sin i for cool giants. They find that if convection zones rotate with depth independent specific angular momentum the observed decrease in v sin i is obtained also theoretically. If on the other hand convection zones rotate as rigid bodies, presumably due to large turbulent viscosity then additional, presumably magnetic, fast braking is required.

Rutten and Pylyser (1982) estimate magnetic braking times from the observed decay times for rotation of main sequence stars in galactic clusters of known ages (Skumanich 1972). They find that these braking times are longer by about a factor of 10 at B-V $\sim$ 0.8 than the giant evolution times. They also argue that the decrease in v sin i is actually more smooth than found by Gray and claim that the decrease can be explained by the changing moments of inertia for the expanding giants.

The question then is whether the steep decrease in v sin i is due to a rearrangement of angular momentum in the deep convection zones as suggested by Endal and Sofia (1979) and Rutten and Pylyser (1988), or whether a fast magnetic braking takes place with increasing depth of the convection zone as favored by Gray (1981,1982) and by Simon and Drake (1989). If fast magnetic braking is responsible we would need an increase in the braking efficiency of the stellar winds at the phase of rapidly decreasing v sin i. This will presumably require higher densities or higher temperatures of the coronae. We might then expect stronger X ray emission at these effective temperatures which would probably also mean higher transition layer emission line fluxes. The larger depth of the convection zone might perhaps lead to stronger dynamo action which could cause such effects. If so this could lead to a larger contribution of magnetic heating.

We will test here whether any of these effects expected to be seen for fast magnetic braking can actually be observed.

We will rediscuss the question of the decreasing v sin i making use of known measured values of v sin i as compiled by Rutten (1987), Simon and Drake (1989), Gray (1989) and Maggio *et al.* (1990). We will also make use of the CIV to CII line flux ratios for giants. We argue that these line flux ratios are larger for large MHD wave contributions to the heating of transition layers (Böhm-Vitense and Mena-Werth 1991a). They are thus an indicator of magnetic activity.

We will discuss in this context the X-ray observations for giants published recently by Maggio *et al.* (1990), which are also a measure for magnetic activity.

1.2. Heating mechanisms for chromospheres and transition layers

Simon and Drake suggest that different kinds of mechanical energy input may be responsible for the heating of transition layers in F stars and in G stars.

In a separate paper (Böhm-Vitense & Mena-Werth 1991a) we have also studied the question of different heating mechanisms for different stars. We found that for giants large C IV/C II line flux ratios correlate with high rotation velocities and some small optical light variations indicative of large starspots. We showed that large $R_{CIV} = F(C\,IV)/F(C\,II)$ line flux ratios are also correlated with large transition layer emission line fluxes. Here "large" R_{CIV} means about 2.5 as opposed to 1.25 for socalled "low" values of R_{CIV}. Large R_{CIV} values also correlate with temperature increases in the high photospheric layers by up to 300 K as indicated by an increase in the continuous flux for wavelengths around 1950 Å. This temperature increase was attributed to heating by magnetohydrodynamic (MHD) waves rather than to acoustic waves, because acoustic waves cannot deliver their energy in the high photospheric layers where they have not yet steepened to shockwaves. Heat conduction down from the chromosphere does not supply enough energy. We therefore argue that "large" values of R_{CIV} are indicative of mainly MHD wave heating in the transition layers while smaller values of R_{CIV} show a smaller contribution of this heating mechanism.

From the theoretical point of view different line flux ratios may be expected for different heating mechanisms but not for different fluxes of the same kind (Böhm-Vitense 1987). Only different heating mechanisms have different height dependences of the energy input leading to different temperature gradients in layers with different temperatures. The C II and C IV lines originate at very different temperatures, about 30,000 K and 10^5 K. Their flux ratio is independent of changes in the carbon and nitrogen abundances. Measured values of R_{CIV} can therefore be indicative of the heating mechanism at work.

1.3. Surface element abundances in giants

Sweigart and Mengel (1979) emphasized already that increased N/C abundance ratios are found for giants at the same T_{eff} where v sin i decreases. Deep mixing might therefore be responsible for the decrease in v sin i.

Changes in surface abundances occur in the HR diagram near the knee at the bottom of the red giant branch (see Brown 1987 for observations in M67 and Böhm-Vitense & Mena-Werth 1988, 1991b, and Lambert & Ries 1981 for observations of field giants), when convection becomes very efficient and rapidly extends the depth of the convection zones which then reach deep down into the envelopes close to the hydrogen burning shell sources.

Previously C and N abundances in cool giants were determined from photospheric molecular lines which can, however, for giants only be analyzed for $T_{eff} \lesssim 5000$ K.

From the transition layer emission lines we determine these abundances also for higher temperature giants (Böhm-Vitense & Mena-Werth 1991b) and thereby determine a fairly accurate value for the T_{eff} at which the N/C abundance ratio increase. We can then see at which point and how fast the convection zone extends into the region where CNO nuclear processing has occurred.

2. The Observations

2.1. Rotational velocities of giants

In Table 1 we have listed giants for which reliable data for the rotational velocities v sin i are available. We have relied on the compilations by Rutten (1987), by Simon and Drake (1989), Maggio *et al.* (1990) and Gray (1989). For the stars in Table 1 we also know either C II and/or C IV line fluxes or X-ray fluxes. These stars are all field giants though they include the Hyades giants. They are expected to have had nearly solar element abundances while on the main sequence.

For a narrow range in absolute magnitudes they should also be of comparable ages except for B-V $\gtrsim 1.1$ where the population II red giant branches and the population I giants appear in the same part of the HR diagram. Population II giants are rare in the field. Some old population I giants could however be enclosed in our sample of the coolest giants.

Many of the giants studied here are spectroscopic binaries. If we were to omit all these stars the statistics would become too poor. We therefore keep many of these stars in the sample (except if they have an F star companion) but list their peculiarities. We have to keep this in mind for the discussions.

We have, in Table 1, omitted stars for which only upper limits of v sin i are available or stars for which the uncertainties appear to be larger than about 50%. For random orientation of the rotation axes $\overline{\sin i} \sim 0.8$. If we assume sin i = 1 the average error in v should be $\Delta \log v \sim 0.1$.

In Figure 1b we have plotted the log (v sin i) as a function of log T_{eff}, where T_{eff} has been derived from the B-V colors, using the calibration of Böhm-Vitense (1981) and Flower (1977). If we assume that during expansion each mass element conserves its angular momentum (case 1 of Gray and Endal) we expect the angular momentum ω to vary as $\omega \propto \frac{1}{R^2}$ and $v \propto \frac{1}{R}$ (see also Endal & Sofia 1979). With $R^2 \propto \frac{L}{T_{eff}^4}$ we find for evolution with roughly L $\sim$ const that $v \propto \frac{1}{R} \propto T_{eff}^2$. While many of the stars with B-V $\lesssim 0.8$ follow this line many others do not. There are several stars with B-V < 0.5 which fall below the T_{eff}^2 relation. Most of these stars are known spectroscopic binaries or are suspected to have variable radial velocities. We therefore suspect that these stars may possibly be all close binaries and that their rotational velocities decrease during their evolution because of braking by binary interaction. There may, of course, also be some stars which started out with a lower rotation velocity on the main sequence. Several stars first follow the relation $v \propto T_{eff}^2$ but for B–V ~ 0.8 we find a steep decrease in rotational velocities as found by Gray, reaching a minimum around B-V ≈ 0.98 to 1.00. For still larger B–V only a few stars like the RS CVn stars still have or achieve higher rotational velocities supposedly due to binary interaction. λ And seems to be one RS CVn star with low v sin i but only an upper limit of v sin i < 19 km s^{-1} is known. These stars probably never reach very low v sin i. Binary interaction may prevent this. If they should reach low v sin i they are possibly not identified as RSCVn's because of their relatively low emission line fluxes at this stage.

Most of the stars which have experienced the rapid decrease in v sin i are classified as CH or CN peculiar because of their peculiar molecular band strengths. They are indicated by the symbol p in Figure 1.

A small group of stars experiencing some decrease in v sin i already for B-V ~ 0.7, does not seem to show the peculiar molecular band strengths. Perhaps these stars have slightly different masses than the other stars.

2.2. Transition layer emission line fluxes

In Table 1 we also give the observed C II (1335 Å) and C IV (1550 Å) emission line fluxes. The data are based on the compilations by Simon and Drake (1989), Rutten (1987) and the data of Böhm-Vitense and Mena-Werth (1991a). Uncertain values are indicated by brackets.

In Figure 1a we have plotted the C IV surface fluxes as a function of T_{eff}. As was discussed by Simon and Drake the emission line fluxes are nearly independent of T_{eff} for B-V < 0.75 or $T_{eff} \gtrsim 5600$ K. For lower T_{eff} a steep decrease in the emission line fluxes is seen parallel to the decrease in v sin i. For temperatures below ~4700 K only RS CVn stars still have C IV emission line fluxes comparable to the early G giants. (The behavior of the C II lines is similar to the one of the C IV lines, because the differences in the C IV/C II flux line ratios are only a factor of 2 at most.)

We see no indication for increased transition layer emission at the phases of fast decrease of v sin i. This means we see no indication of increased dynamo activity.

2.3. Ratios of the C IV to C II emission line fluxes

As discussed by Böhm-Vitense and Mena-Werth (1991a) the ratio $R_{CIV} = \frac{F(CIV)}{F(CII)}$ can give us information about the heating mechanism for the transition layers and chromospheres. We have therefore in Figure 1c also plotted $\log R_{CIV} = \log \frac{F(CIV)}{F(CII)}$ as a function of T_{eff}.

The scatter in this graph is large. Comparing different measurements of emission line fluxes for the same spectra we find differences of $\Delta \log F \sim 0.1$, telling us that this is the uncertainty of the flux measurements. For the flux ratio an uncertainty of at least 0.2 dex may therefore be expected. Nevertheless some general trends may be recognized in Figure 1c: Looking first at the F and early G giants we see a decline in R_{CIV} parallel to the decline in v sin i for the spectroscopic binaries and a few other stars with lower v sin i.

Notice that some of the stars seen in Figure 1b are missing because of uncertain or unknown flux measurements. The decrease in R_{CIV} indicates, in our opinion, (see Böhm-Vitense & Mena-Werth 1991a) a decrease in the MHD wave heating contribution.

The R_{CIV} values remain high for the stars whose rotation follows the $v \propto T_{eff}^2$ relation but then drop also for $\log T_{eff} < 3.7$ when the v sin i drop for all stars. This in our opinion again indicates that the contribution of MHD wave heating decreases when v sin i drops. There is again no indication of increased activity due to the larger depth of the convection zones. One RS CVn star is found with a moderately low R_{CIV} value, which can, however, be just due to the uncertainty in the measurements. Otherwise it seems that for RS CVn and FK Comae stars MHD wave heating is always the main contribution to the heating.

In Figure 1c the point for γ Tau was omitted because the C IV line appears to be highly variable as seen from Figure 2 where we compare 4 low resolution spectra of γ Tau taken by different observers at different times but with similar exposure times. For this star the smallest R_{CIV} value is observed for the lowest continuum flux around 1950 Åin the spectrum SWP 27912.

For the stars with $\log T_{eff} > 3.8$ the surface line fluxes do not follow the trend of the R_{CIV} as seen when comparing Figures 1a and 1c. One might expect that for decreasing MHD wave heating the line fluxes might decrease. It appears, however, that for F giants the acoustic flux generation and deposition increases with decreasing T_{eff} because of the increasing densities and extends of the convection zones (see also Bohn 1984 and Gilliland 1986). This seems to compensate for the decreasing MHD wave heating.

2.4. Nitrogen and Carbon surface element abundances

In Figure 3b we have plotted as a function of T_{eff} the surface abundance ratios of N/C as determined by Lambert and Ries (1981) from photospheric molecular bands (strong enough CN bands are only seen for $\log T_{eff} < 3.70$) and as determined by Böhm-Vitense and Mena-Werth (1988, 1991b) from transition layer emission line fluxes. (For consistency we use here for the Lambert-Ries stars also the $T_{\rm eff}$ as determined from the B-V colors, rather than using the $T_{\rm eff}$ given by Lambert and Ries. In essence we plot everything as a function of B-V.)

Böhm-Vitense and Mena-Werth determine changes in the N/C ratio as compared to main sequence stars. As seen in Figure 3b they then find for most F and early G giants $\Delta \log \frac{N}{C} = 0 \pm 0.15$. β Cas and a few other stars are exceptions. (β Cas is a δ Scuti star. The emission line strengths may be influenced by pulsation. If so our method of analysis is not applicable and the derived N/C abundance ratio is probaly in error. The CIV line is unusually strong ,leading to the apparently low nitrogen abundance determination). Lambert and Ries determine abundances only for cool stars with molecular bands. They determined values of C/H and N/H from which we determined the N/C abundance ratios. Δ log N/C can then be obtained from the adopted main sequence value for N/C. A solar value $(C/N)_\odot = 4.8$ was given as reference value by Lambert and Ries. We adopted for our studies a somewhat lower value, namely $(C/N)_{MS} = 3.16$. This gives a better representation of the emission line fluxes for main sequence F stars. It is also the solar abundance ratio given by Anders and Grevess (1989). For a given star the Lambert and Ries values for Δ log N/C come out larger by about 0.15 which can be attributed to the different values of $(\frac{C}{N})_{\rm MS}$ used for the two data sets.

The observed increase in the N/C abundance ratio is in rather good agreement with the one predicted by theoretical studies by Sweigart, Greggio and Renzini (1989) as shown by the solid line in Figure 3b. We notice, however, that larger N/C ratios are already observed for some stars with $\log T_{\rm eff} > 3.71$. This might be partly due to lower masses of the stars. According to the calculation by Sweigart *et al.* increases in the N/C abundance ratios start to occur at somewhat lower $T_{\rm eff}$ for stars with somewhat lower masses.

Unexplained are the higher N/C abundance ratios observed for some stars with $\log T_{\rm eff}$ around 3.82. If this anomaly is confirmed by additional observations it may show that these stars are descendants of Am or Ap stars (Wheeler 1991) whose surface abundance in carbon was reduced presumably due to diffusion. (Some Ap stars also show reduced surface carbon abundance). If so this anomaly should disappear when the convection zone increases in depth. This may be observed for log $T_{eff} \sim 3.77$. Clearly more observations are needed for this range in T_{eff} .

Also unexplained are the very large N/C abundance ratios ($\sim$10) seen for some stars with log $T_{eff} \lesssim 3.73$. Maybe these are clump stars which have experienced some additional mixing during the helium flash or maybe they have experienced mass transfer from an evolved star?

In any case while there are a few peculiar stars like DK UMa (classified as RS CVn star by Kholopov 1985 but as a pulsating star by Henriksson 1977), or HR9024, a strong emission line star, the Δ log N/C increase generally for log $T_{eff} \lesssim 3.72$ where we observe the decrease in v sin i as seen by comparison with Figures 1b and 3b. It is interesting to note that DK UMa does actually have a higher N/C abundance consistent with its low v sin i. Either it was mixed at a somewhat earlier state of evolution than the other stars (perhaps it has a lower mass) or its B-V does not indicate its real T_{eff} and it is actually cooler. HR9024 seems to be at an evolutionary stage where it is just being mixed. The RS CVn star λ And apparently is not deeply mixed. Perhaps a stronger magnetic field may suppress the efficiency of convection in this star or its B–V does not indicate its correct T_{eff}. Its v sin i is <19 km s^{-1} and is probably mainly determined by tidal interaction. It appears to be metal deficient (Helfer and Wallerstein 1968) and therefore probably of low mass.

2.5. X-ray observations

Observed values for X-ray fluxes f_x have been collected by Maggio *et al.* 1990. We have determined angular diameters for the giants by means of the Barnes-Evans method (Barnes-Evans 1976) and calculated surface fluxes, as given in Table 2.

On the sun X-rays are preferentially emitted in coronal loops (Rosner, Tucker and Vaiana 1978). If the same holds for the giants then we may expect that X-ray emission increases with increasing dynamo strength which means with increasing v sin i, as is generally thought.

We see no indication of increased X ray fluxes at the phase when v sin i drops. We thus see no indication for increasing dynamo strength and stellar winds. In Figure 3c we find a steep decrease in X-ray fluxes for stars with log $T_{eff} \lesssim 3.72$ in near agreement with the T_{eff} for the steeply decreasing v sin i values (log $T_{eff} \sim 3.683$). We notice however, that at least one star, DK UMa, has already a low v sin i while its X-ray flux is still high. Because of the uncertainty in sin i we cannot be absolutely certain that its rotation velocity has indeed decreased, though the low value of R_{CIV} supports this assertion. If so, it means that the fields mainly responsible for the coronal X-ray emission have decay times longer than the decay time for the rotation velocity and for the R_{CIV}.

The stars with the low X-ray fluxes all have low v sin i and low F(CIV). To our surprise we do, however, also find a fairly large number of stars in the same T_{eff} range including several RS CVn stars which have a 10 times higher X-ray surface flux than most of the stars with $3.65 <$ log $T_{eff} < 3.70$ and about 100 times more X-ray surface flux than β Gem and ε Cyg. Not all of these stars are close binaries. γ Tau has an X-ray flux 3 times higher than corresponding to its low v sin i values, suggesting that at least sometimes it has some unusual activity.

It is interesting to note that the otherwise apparently similar 3 Hyades giants show very different X-ray emissions, δ and θ^1 Tau differing by almost a power of 10, yet their v sin i values are very similar.

3. Interpretation of the Observations

3.1. Reduction of rotation by deep convection

The compilation of well known v sin i values here confirms the conclusions by Endal and Sofia and by Rutten and Pylyser that for giants the decrease in rotation velocities for stars with log $T_{eff} > 3.7$ is generally due to the expansion of the stars along the giant branch. At the base of the ascending red giant branch deep mixing occurs due to the increasing depth of the convection zone as expected theoretically and as verified by the increase in the N/C abundance ratios. The decrease in v sin i occurs at the same T_{eff}.

The coincidence of the decrease in v sin i and the deepening of the convection zones is strong support for the conclusion that this decrease is due to mixing. The temperature for which the convection zones reached deepest into the star agrees with the temperature for which the low v sin i are reached, (see Figures 3a and 1b), and where the highest N/C abundance ratios are reached (see Figure 3b). If we assume that before mixing the star was rotating approximately as a rigid body then the deeper layers have a much lower angular momentum than the surface layers. Convection transports this low angular momentum material to the surface leading to the lower surface rotation. The close agreement between the observed decrease in v sin i and the one calculated by Gray and Endal 1982 for the case of depth independent specific angular momentum for stars of 2.5 and 3 $M_\odot$ (see the squares in Figure 1b) shows that the convection zones rotate most probably in this mode, at least during the time of increasing convection zone depth. Given enough time it may perhaps be possible for turbulent viscosity to influence the angular momentum distribution somewhat. This might perhaps lead to the slight increase in v sin i which seems to be observed for some of the cooler, apparently single giants. If the slight increase in v sin i for the cooler single stars can be verified by more observations this would be a strong argument against magnetic braking. At present the evidence is too weak to use this argument.

For these low T_{eff} we may also see stars of lower masses and larger ages. Gray and Endal's calculations give slightly higher v sin i for lower mass stars, if they start out with the same v sin i at the main sequence. Lower mass main sequence stars do, however, have lower v sin i when they leave the main sequence than the A stars. They are then expected to have lower v sin i than the more massive stars when they start to climb up the red giant branch. While this question is not settled it seems that the possibly higher v sin i for single stars with log $T_{eff} \sim 3.68$ cannot be understood in this way.

3.2. Fast magnetic braking of rotation?

Rutten and Pylyser estimate magnetic braking times of about $5 \cdot 10^7$ years for giants with B–V $\sim$ 0.8 while for several stars the decline of v sin i happens in about 3 million years as seen from a comparison of Figures 3a and 1b. Faster magnetic braking might be expected for larger magnetic activities of the giants which could perhaps be caused by the deeper convection zones. There is no sign of increased magnetic activity at log $T_{eff} \sim 3.75$. The decreasing CIV/CII ratio of emission line fluxes indicates decreasing magnetic activity parallel with the decrease in v sin i. Transition layer emission line fluxes also decrease as seen in Figure 1a. Increased coronal activity would be expected to show up in the X-ray emission, which does, however, also decrease at these evolutionary phases. There is therefore no observed indication for increased magnetic activity at this phase of giant evolution and therefore no observational basis for the hypothesis of fast magnetic braking at this phase.

We conclude that the rearrangement of angular momentum in a rapidly deepening convection zone rotating with nearly depth independent specific angular momentum is the most likely explanation for the rapidly decreasing rotational velocities in giants.

We want to emphasize that we do not claim that the decreasing v sin i for later spectral types along the main sequence are due to a similar reason. Main sequence stars with chromospheres and coronae stay on the main sequence long enough that magnetic braking can reduce their angular momentum. The depth of the convection zone does not change for each star during its main sequence lifetime. For giants the situation is very different.

3.3. X-ray emission

The X-ray emission does not appear to be very closely correlated with v sin i. While for some of the stars with log $T_{eff} < 3.71$ the X-ray emission decreases as expected it does not do so for many other stars. According to Maggio *et al.* 15 out of 17 detected X-ray sources are multiple systems. In addition to the points shown in Figure 3c there are several upper limits determined for KO III stars which are below the value measured for β Gem. It seems therefore possible that the measured X-ray fluxes refer all to binaries and are higher than the X-ray fluxes for single stars in the temperature range for the low v sin i. Why the multiple cool star systems should show a much higher X-ray flux than single stars with the same v sin i is not obvious to us, especially since their C II and C IV line fluxes do not seem to be much higher. It also remains a puzzle why there should be such a rather tight sequence of stars with many RS CVn stars on it emitting just about a factor of 10 more X-rays than the other stars. They appear to escape the phase of steep X-ray decline and instead seem to follow their own sequence of slowly declining X-ray emission as seen in Figure 3c. Are we permitted to speculate that perhaps their X-rays do not originate in their coronae proper?

4. Summary

The sharp decrease in v sin i for giants with B-V < 0.8, is most likely attributable to the rather sudden increase in depth of the hydrogen convection zone at the evolutionary phase when the giants start to ascend the red giant branch. Low angular momentum material has been brought to the surface also having a higher N/C abundance ratio.

We see no indication of increased magnetic activity which could lead to fast magnetic braking for giants with B–V ~ 0.8.

For log $T_{\rm eff} < 3.67$ it seems possible that the v sin i recover slightly for some stars. It is not clear at present whether this might be true for binaries only. In single stars it could possibly be due to a partial return to rigid rotation because of turbulent friction.

Due to lower v sin i the MHD wave heating of the transition layers decreases, leading to smaller emission line fluxes and to changes in the temperature stratification in these layers which are then mainly heated presumably by acoustic flux. The change in temperature stratification in the transition layers causes a reduction in the C IV/C II line flux ratios.

The decrease in v sin i leads to a steep decrease in X-ray emission for some stars but not so much for others. Binary nature may prevent a steep decrease in X-ray fluxes.

RS CVn stars do not show a steep decline in X-ray emission at the mixing phases. From the available data we do not know whether their transition layer emission decreases steeply at these phases.

Some other points may be of interest:

If the decrease of surface rotation velocity is due to rearrangement of angular momentum in the convection zone then we must find a large gradient of rotational velocity at the bottom of the convection zone which will probably lead to other instabilities and may extend turbulent mixing to layers below the convection zone proper. This may perhaps explain the unexpectedly large N/C abundance ratios observed for some stars.

If the decrease in surface rotation velocity is not due to braking then the total angular momentum is conserved, yet the magnetic activity decreases. This then shows that the observed magnetic activity is due to magnetic fields generated in the high layers of the convection zone.

Since the X-ray fluxes, presumably concentrated in coronal loops, also decrease with decreasing surface rotation but constant overall angular momentum we must conclude that even the large scale magnetic fields seen in the loops are generated in the high layers of the convection zone. If the slight delay in the decrease of the magnetic fields as compared to the decrease in surface rotational velocity, suggested in Figure 3 especially by DK U Ma, is real (this clearly needs more observations to confirm), then this indicates that these large scale fields take a time on the order of 10^5 years to decay.

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Table 1
Data for observed stars with known v sin i

Star	HD	B-V	Sp. type	log T_{eff}	v sin i	F(CII)	log F(CIV)	log F_x	Remark	log(v sin i)
β Cas	432	0.34	F2 III-IV	3.858	70.0	4.91	5.29	4.49	SB	1.845
	483	0.70	G2 III	3.743	52.0	4.50	4.88			1.716
β Cet	4128	1.02	K0 III CH-1	3.675	3.0	3.42	3.42	4.89		0.477
ψ^3 Psc	6903	0.69	G0 III	3.745	95.0	5.04	5.40	5.08		1.978
	8634	0.43	F5 III	3.822	34.0			5.88	SB	1.532
16 Per	17584	0.34	F2 III	3.857	149.0	4.78	(5.04)	?		2.173
γ Tau	27371	0.99	K0 III ab CN1	3.681	2.4	3.07	3.45	4.57	SB	0.380
δ^1 Tau	27697	0.98	K0 III CN 0.5	3.683	2.5	2.91	?	4.03	SB	0.398
ϵ Tau	28305	1.01	G9.5 III CN 0.5	3.677	3.0	2.87	2.70	?		0.477
θ^1 Tau	28307	0.95	K0 III b Fe 0.5	3.691	3.4	3.66	3.76	4.94	SB	0.532
HR1889	36994	0.43	F5 IV	3.822	76.0	5.16	5.42	?		1.881
45 Aur	43905	0.43	F5 III	3.822	20.0	4.97	5.06	?	SB	1.301
π C Ma	51199	0.37	F2 III	3.845	120.0			5.14		2.079
25 Mon	61064	0.44	F6 III	3.818	25.0	5.09	5.18	?	V?	1.398
o Gem	61110	0.40	F3 III	3.833	90.0	5.11	5.35	?	V	1.954
σ Gem	62044	1.12	K1 III	3.656	22.0	4.70	4.90	6.05	SB, RS	1.342
β Gem	62509	1.00	K0 IIIb	3.679	2.5	2.49	2.67	2.82	V	0.398
α Cha	71243	0.39	F5 III	3.836	36.0			5.43		1.556
o UMa	71369	0.85	G5 III	3.715	2.6	3.62	?			0.415
35 Cnc	72779	0.68	G0 III	3.748	87.0	5.36	5.76		V	1.940
24 UMa	82210	0.77	G4 III-IV	3.732	4.9	4.44	4.43	6.11	DK UMA	0.690
18 Com	108722	0.43	F5 III	3.822	93.0	5.35	5.65		SB	1.969
31 Com	111812	0.67	G0 IIIp	3.750	85.0	5.22	5.52	6.06	V?	1.929
ϵ Vir	113226	0.94	G8 IIIab	3.694	2.7	3.08	3.20	3.95		0.431
ι Vir	124850	0.52	F6 III	3.794	16.0	4.78	4.88			1.204
μ Vir	129502	0.38	F2 III	3.841	46.5	(5.28)	5.30	5.89	SB	1.668
β Her	148856	0.94	G7 IIIa	3.694	3.4	3.18	3.30	4.13	SB	0.532
η Her	150997	0.92	G8 IIIb CN-1	3.696	8.0	3.47	3.63		V?	0.903
ϵ UMi	153751	0.89	G5 III	3.704	23.0	4.31	4.71		SB, RS	1.362
oDra	175306	1.19	G9 IIIb CN-0.5	3.636	20.0	3.60	3.89	4.11	SB	1.302
α Sge	185758	0.77	G1 III	3.733	5.2	4.28	<4.23			0.716
ϵ Cyg	197989	1.03	K0 III	3.671	3.0	3.10	2.83	<3.05	SB	0.477
HR 8191	203842	0.47	F5 III	3.809	84.0	4.93	5.14	<5.25	V?	1.924
31 Cep	214470	0.39	F3 III-IV	3.836	85.0	4.64	4.87			1.929
HR 8703	216489	1.12	K1-2, II-IIIe	3.656	7.0	4.89	5.30	6.18	IM Peg, RS	0.845
π Cep	218658	0.82	G2 III	3.722	4.7	3.99	<4.29		SB	0.672
υ Peg	220657	0.61	F8 III	3.768	79.0	5.08	5.30	5.76		1.898
HR 9024	223460	0.79	G1 IIIe	3.728	20.0	5.00	5.43		FK?	1.302

Figure Captions

Figure 1a. The dependence of the C IV (1550 Å) emission line surface fluxes on the effective temperature is shown for giants. Dots indicate known spectroscopic binaries, v indicate variable radial velocities and question marks possible variable radial velocities for the stars. RS indicates RS CVn stars, p stars with peculiar CN and/or CH molecular band strengths. Brackets signal uncertain measurements, and arrows show that the values given are upper limits.

Figure 1b. The measured rotational velocities v sin i are shown as a function of T_{eff} or B-V. T_{eff} scale is the same as in Figures 1a and 1c. Notation as in Figure 1a. Notice that the peculiar CN and CH molecular band strength are observed only after the stars have decreased their v sin i.

The dashed line indicates the expected decrease in v sin i due to expansion if each mass element were to conserve its angular momentum (see text).

The values calculated by Gray and Endal (1982) for v_0 sin i = 140 kms^{-1} and for depth independent specific angular momentum in the convection zones are given as squares.

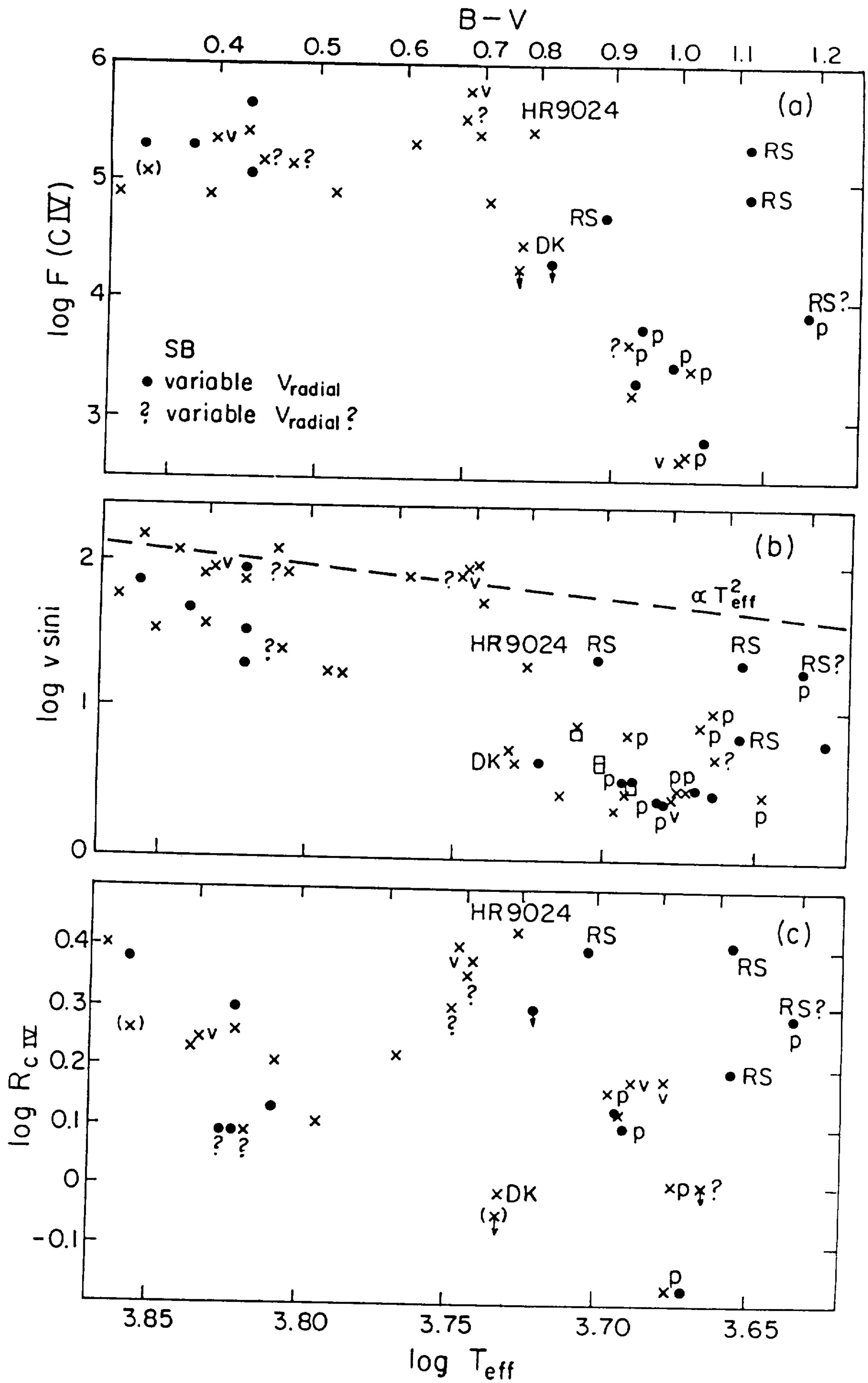
Figure 1c. The logarithm of the C IV to C II line flux ratio $R_{CIV} = \log \frac{F(CIV)}{F(CII)}$ is shown as a function of log T_{eff}. Notation is the same as in Figure 1a. The ratio decreases for slowly rotating stars, probably showing a smaller contribution of MHD wave heating. γ Tau was omitted from the plot because of the large variations in R_{CIV}.

Figure 2. Different spectra of γ Tau are shown displaying the large variations in the appearance of the C IV line at 1550 Å. Other spectral changes appear to be present also. The different spectra are displaced upward by 0.6 E-14 each.

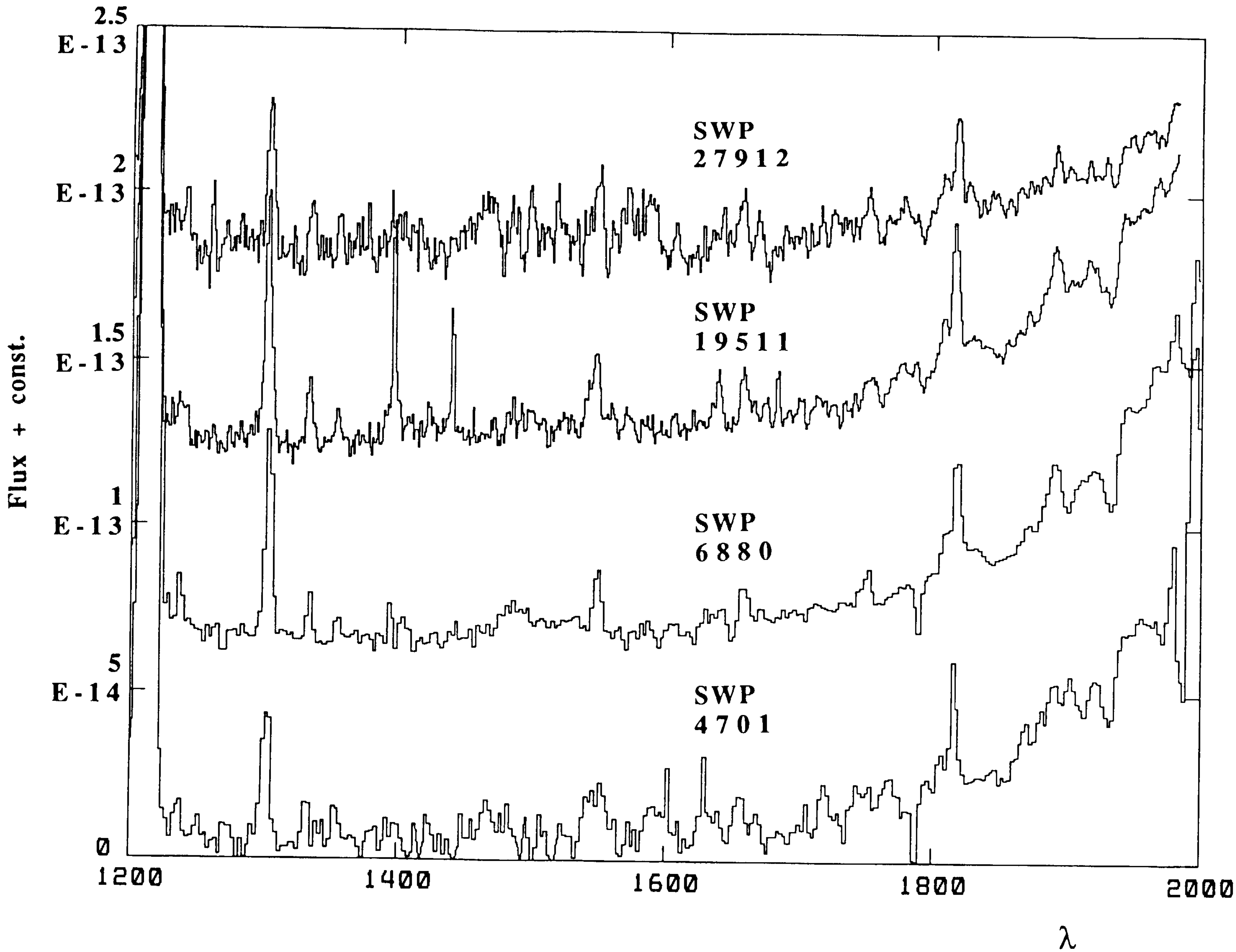
Figure 3a. The theoretical evolutionary track of a 2.2 $M_\odot$ star is shown in the T_{eff}, luminosity diagram (right hand scale). Also plotted is the age t as a function of T_{eff} (left hand outer scale) and the depth of the convection zone, measured by the mass M_{CE} [$M_\odot$] (left hand inner scale) below the lower boundary of the convection zone. The point E gives the evolutionary phase with the largest depth (in mass) of the convection zone. Data are from Sweigart, Greggio and Renzini (1989).

Figure 3b. The observed changes in abundance ratios of nitrogen to carbon N/C, as compared to main sequence abundances, are plotted as a function of T_{eff}. The point for the δ Scuti star β Cas at log $T_{eff} \sim 3.86$ lies at Δlog N/C $= -0.24$.

Figure 3c. Plotted as a function of T_{eff} are the X-ray surface fluxes as calculated from the data given by Maggio *et al.* (1990). Notation as explained in the figure. The symbols δ, γ and θ refer to the Hyades giants.

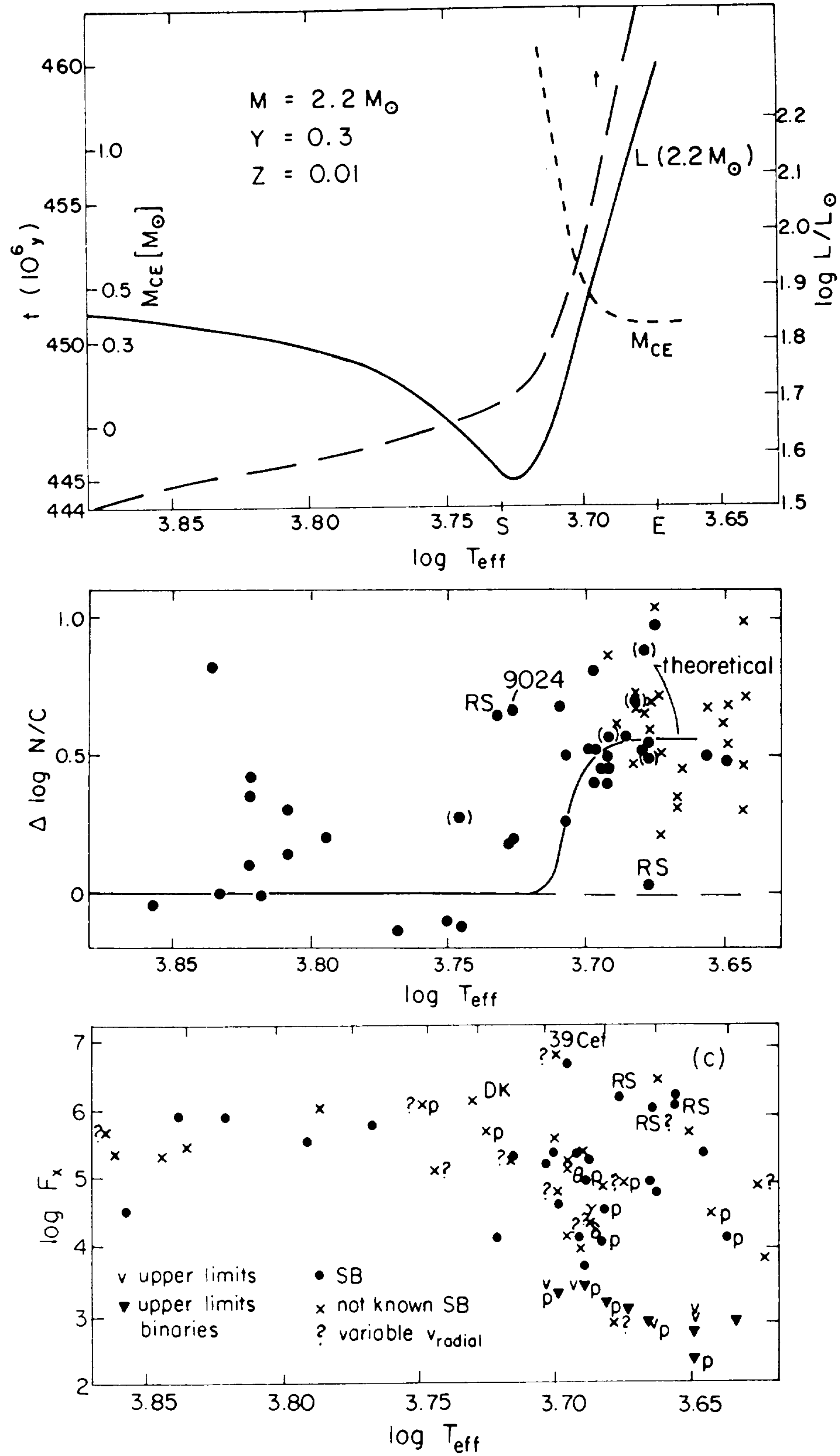


B − V
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
log F (C IV)
(a)
HR9024
RS
RS?
DK
SB
variable V_{radial}
variable V_{radial}?
log v sini
(b)
$\alpha\ T_{eff}^2$
log $R_{C\ IV}$
(c)
3.85
3.80
3.75
3.70
3.65
log T_{eff}



2.5
E-13
2
E-13
1.5
E-13
1
E-13
5
E-14
0
Flux + const.
SWP
27912
SWP
19511
SWP
6880
SWP
4701
1200
1400
1600
1800
2000
λ

Figure 1



M = 2.2 M⊙
Y = 0.3
Z = 0.01
t (10⁶ y)
M_CE [M⊙]
log L/L⊙
L (2.2 M⊙)
t
M_CE
S
E
log T_eff
Δ log N/C
9024
RS
theoretical
RS
log T_eff
log F_x
39 Cef
DK
RS
RS
RS?
(c)
v upper limits
▼ upper limits binaries
● SB
× not known SB
? variable v_radial
log T_eff

Figure 3